Technical Support Package

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'Large, Easily Deployable Structures'

NASA Tech Briefs, Fall 1982
Vol. 7, No. 1, MFS-25647

TECHNOLOGY UTILIZATION OFFICE

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Technical Support Package
For

LARGE, EASILY DEPLOYABLE STRUCTURES

MFS-25647

NASA Tech Briefs, Vol. 7, No. 1

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TABLE OF CONTENTS

1.0 BACKGROUND

This Technical Report presents the results of Phase II of the Erectable Concepts for Large Space System Technology contract NAS8-33431 conducted between March 1980 and January 1981. The original contract was awarded to the Vought Corporation by the Marshall Space Flight Center (MSFC) in April, 1979, and was reported on in Reference (1) in March 1980.

The development of the Space Transportation System and the Shuttle Orbiter created a need for knowledge concerning packaging and construction of space structures. Many systems and techniques have been proposed and studied. This contract was aimed at extending the data base for practical erectable/deployable structures by identifying and analyzing new and previously proposed approaches, structural elements, and joint concepts. The primary conclusion of the Phase I Study was that for near-term missions, such as the Science and Applications Space Platform, the high packaging density obtainable with single member elements is not critical enough to afford the increased cost and complexity of on orbit assembly. These near-term applications, using moderate size structures, could usually accommodate sufficient lengths of deployable structural modules in the Orbiter payload bay. A secondary conclusion of the study was that the incorporation of utilities with the structure may significantly impact the stowage, deployment, and assembly requirements.

The Phase I study culminated in the design, fabrication, and testing of two single-member end attachments, one module-to-module coupler and one 1-1/2 x 1-1/2 x 3 m. double-cell, called half-size, double-folding structural module (Figure 1-1). Four packaging configurations with different form factors were studied. Three of these are shown as 1/10 scale models in Figure 1-2 along with the MSFC design concept, which Vought studied under the same contract. The hybrids are defined as partially deployable, requiring joining or erection operations. The cubic module provides a basic building block adaptable for constructing linear arms and wide area platforms.

As demonstrated by Figure 1-3, which shows the final selected configuration, the models proved extremely useful in visualization and assessment of the operating characteristics. This configuration is fully deployable and may be used in either the single or double-fold modes as required by available stowage space. For this reason the single fold hybrid was dropped from further study, though the "cardtable" concept was recommended as a potential complement to the double-fold as an interconnect between modules.

Figure 1-4 shows the "half size" model constructed in Phase I. This was particularly helpful in assessing joint tolerance, which was reported on in Reference (2). The joints and strut diameters were full scale, with the struts built half length to facilitate handling.

Of the three joint concepts identified in Figure 1-1, the most promising is the module-to-module coupler (discussed further in Section 4). It can be used for a variety of purposes including connecting members and structural modules, or attaching experiment pallets to platforms. Attractive performance features include hard and soft capture capability under axial, lateral and angular misalignment conditions. Linear spring rate (no free play) is obtained automatically as any movement after soft capture brings the probe toward a hard seat.

The other joint concepts shown are uniquely suited to the member by member erectable concepts.

The look at structural member types was also affected by the conclusion that for near term platforms, extreme density packaging was not a design driver. Therefore, simple cylindrical members were used in the remainder of the study because of the structural efficiency of the shape.

Leading to this phase of the contract it was recommended that neutral buoyancy testing of full size hardware and investigation of utilities incorporation be included in the next studies.

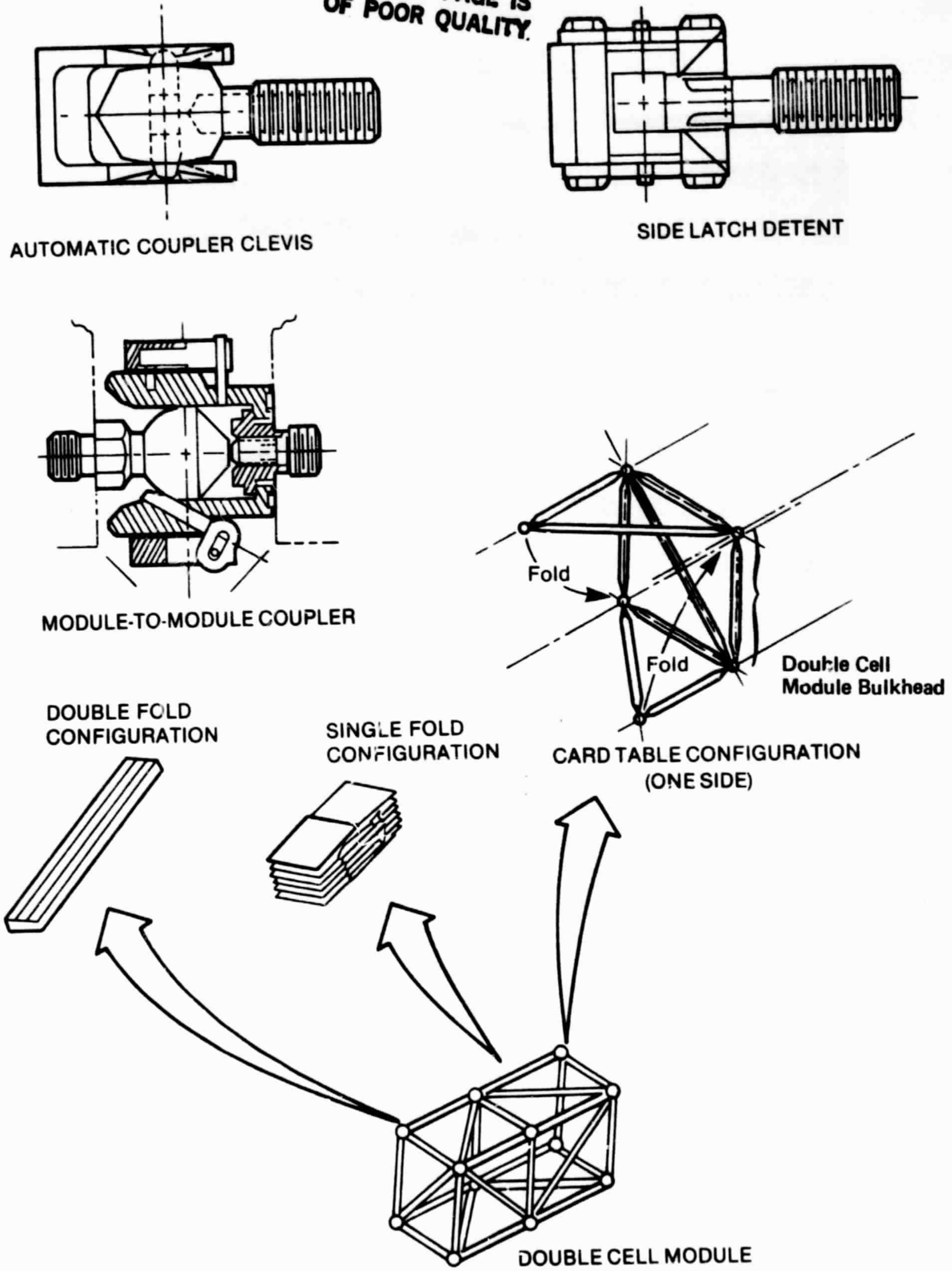

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Figure 1-1 PHASE I SELECTED CONCEPTS

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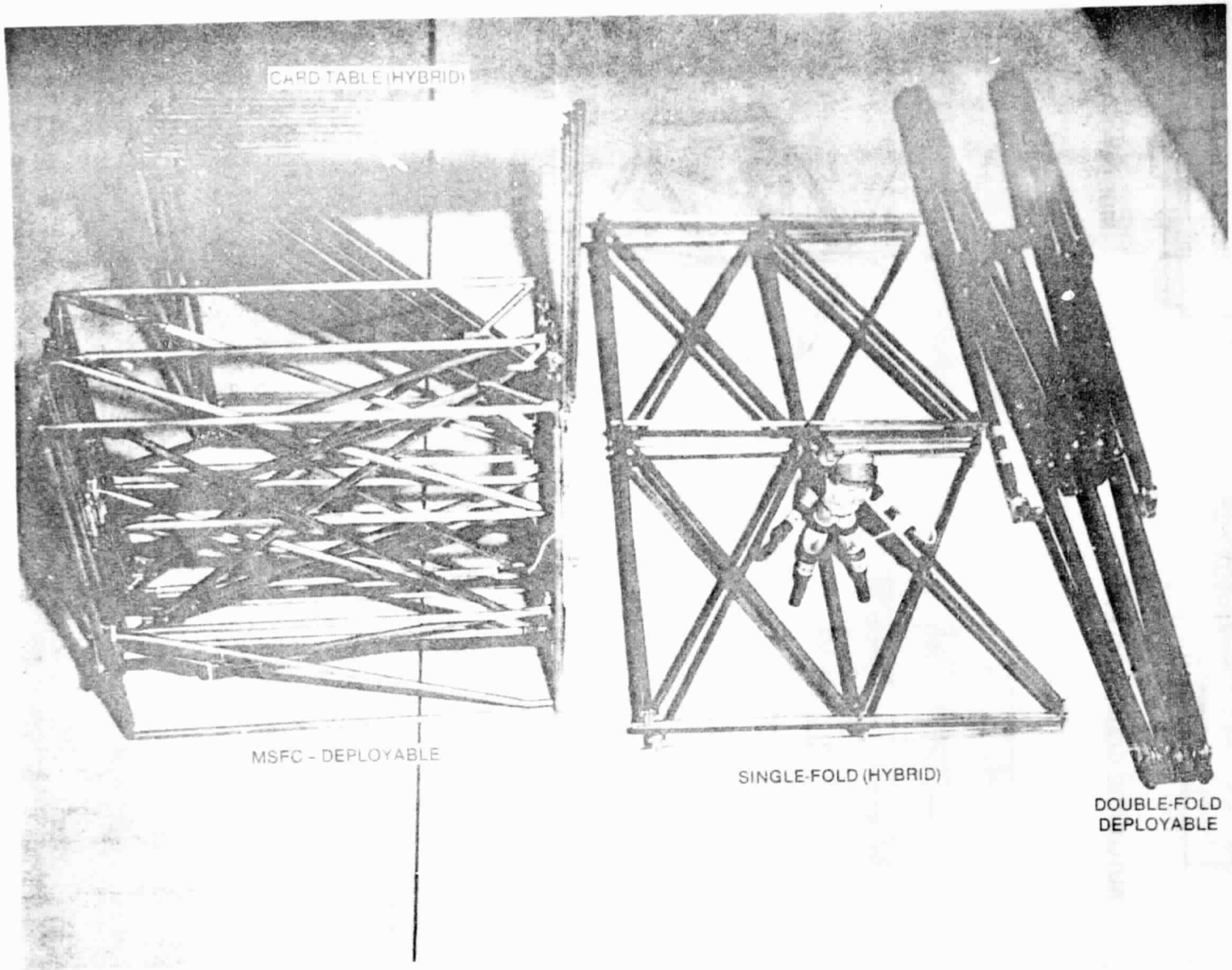

Figure 1-2 1/10 - SCALE ENGINEERING AIDS

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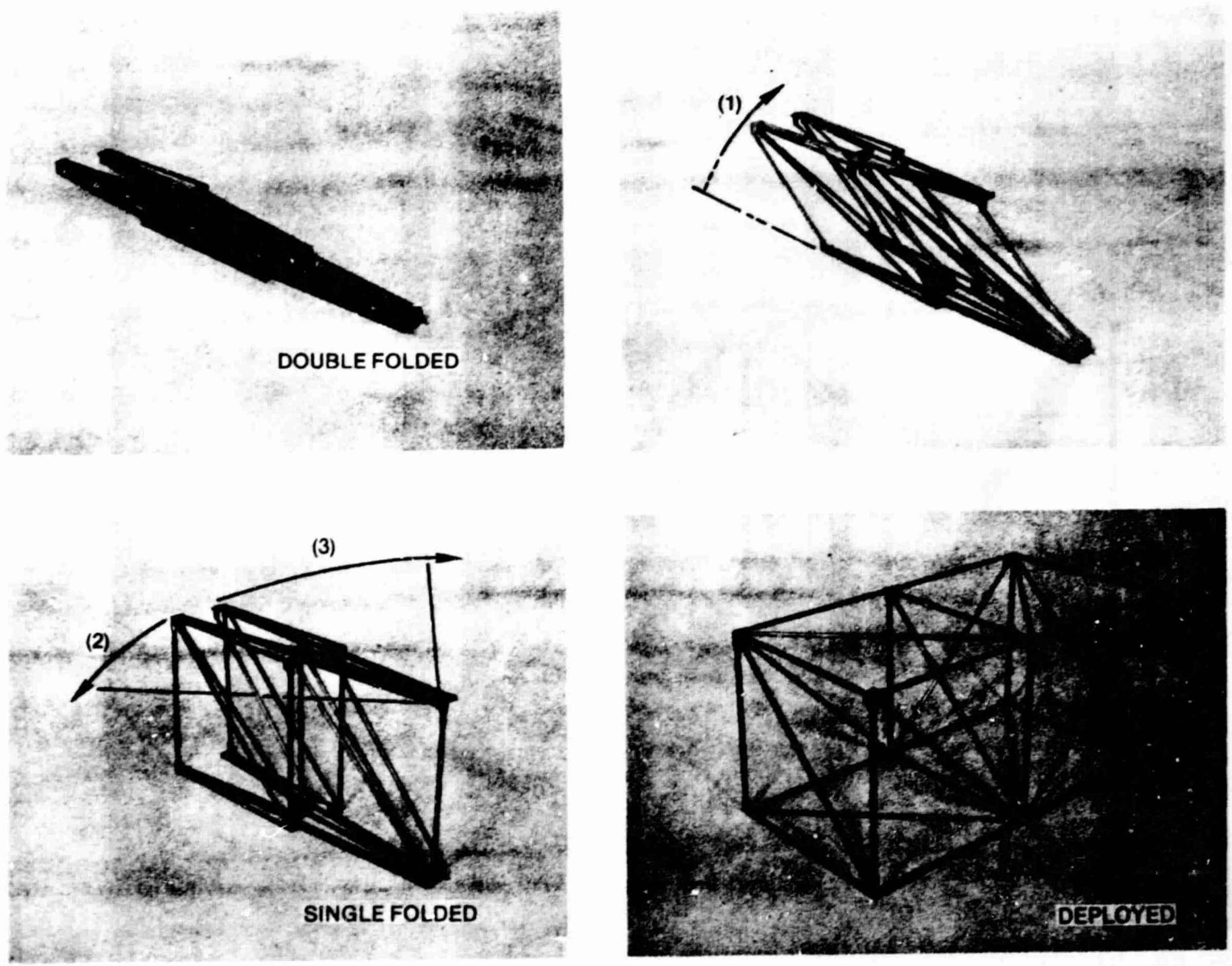

Figure 1-3 DEPLOY SEQUENCE — DOUBLE-FOLD DOUBLE CELL

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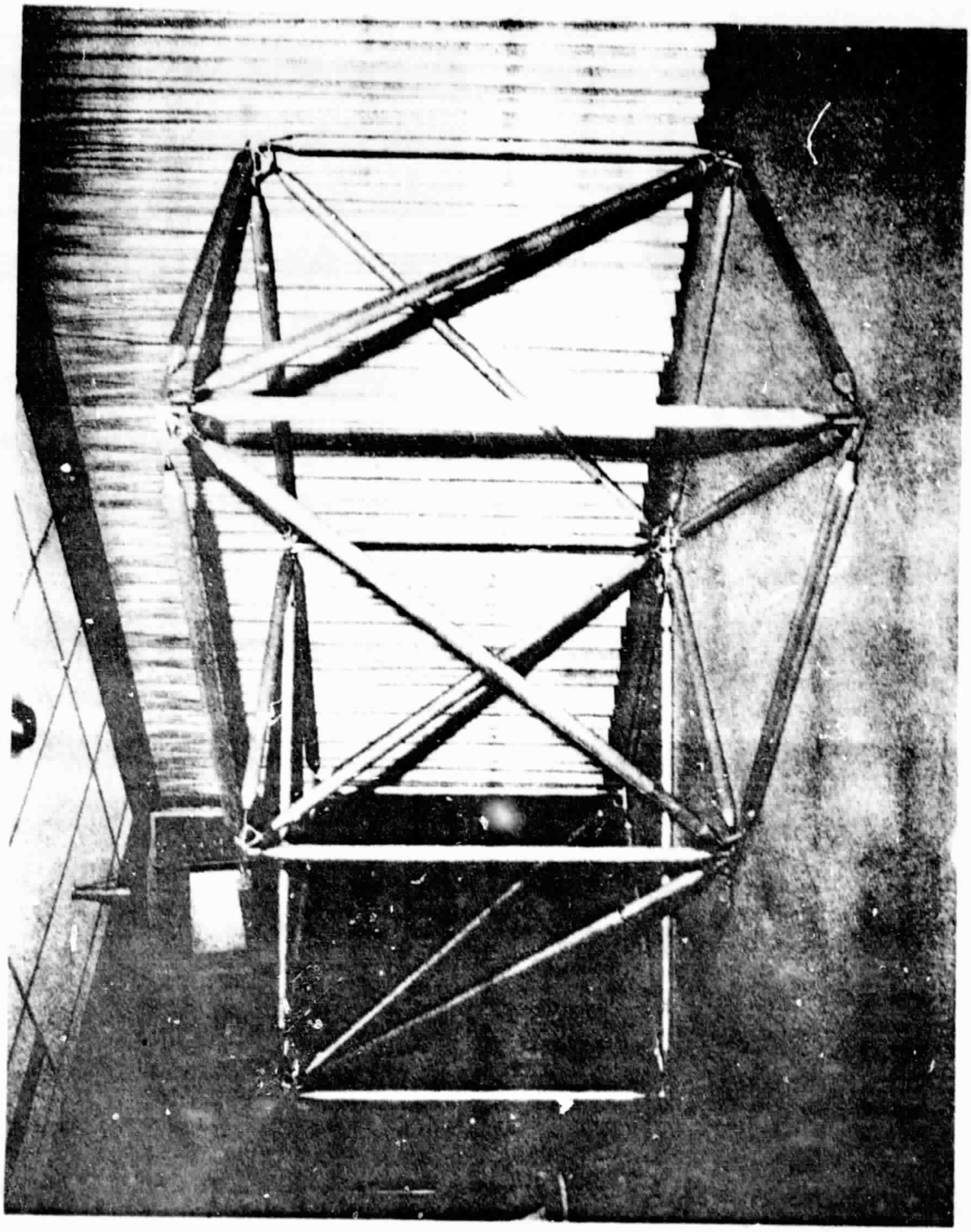

Figure 1-4 "HALF-SIZE" PHASE I MODULE

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2.0 OBJECTIVE

The purpose of the Phase II effort was established as a continuation of the development of the Phase I hardware to provide design and test data for packaging, deploying, and assembling structures for near-term space platform systems, by testing flight type hardware in the MSFC Neutral Buoyancy Simulator.

This involved several specific objectives:

(1) Arrive at an optimum or near optimum structural configuration for varying degrees of deployment utilizing different levels of EVA and RMS.
(2) Refine the design of joints and connectors and their lock/release mechanisms to improve performance and operational convenience.
(3) Further evaluate incorporation of utilities into structural modules to determine their effects on packaging and deployment.
(4) By simulation tests, obtain data for stowage, deployment, and assembly of the final structural system design to determine construction timelines, evaluate system functioning and techniques, and discover any needed improvements in design or procedures.

Tasks added in September 1980 were:

(1) To study feasibility of automatic deployment.
(2) To prepare a preliminary design of an automatically deploying structure.

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3.0 SUMMARY

A Vought/MSFC review of earlier work resulted in selection of Vought's double-fold, double-cell (DFDC) module concept as the basic structural component for further design and simulated zero-g testing, utilizing the automatic coupler clevis and the module-to-module coupler.

3.1 Design

Refinements were made in the module and connector designs to increase the ease of operation of connectors, decrease required module deployment forces, and to minimize joint and hinge free play. The specific design refinements included the incorporation of a release lever and release lockout into the module-to-module coupler and a release mechanism for the automatic coupler clevis. A new lock and release mechanism was designed for the telescoping members to make hand operation by a space suited EVA subject feasible. Teflon bearing pads were added to the telescoping members to decrease deployment and folding forces. Module hinges were modified by replacing solid pins with spring pins to eliminate free play.

3.2 Test Hardware

Structural test hardware was fabricated for simulated zero-g testing in the MSFC Neutral Buoyancy Simulator (NBS). The aluminum test structure was designed to withstand the mildly corrosive water environment and buoyancy chambers were incorporated to provide neutral buoyancy. All of the design refinements for flight hardware were used in the NBS test structure. One of the primary considerations in the test hardware design was the provision for as much flexibility as possible in stowage, deployment, and assembly using a basic module. The resultant hardware allowed either single-fold or double-fold stowage configurations. A variety of deployment and assembly procedures was possible using various combinations of EVA and RMS participation. In addition to two basic double cube modules, a module-to-module interconnect structure was utilized for three purposes:

(1) To permit connection of the modules without having redundant (adjacent) bulkhead members.
(2) Three "Card Table" members were used for assessment of the unfolding operation of a combination erectable/deployable (hybrid) unit.
(3) Two loose members were used for assessment of a fully erectable concept.

A stowage fixture was designed and fabricated for holding the test structure in the payload bay of the NBS Orbiter mockup. This fixture was adaptable for stowage and deployment of the modules in either single-fold or double-fold configurations. A base frame was built to provide an attachment point for the deployed structural modules at the rear of the payload bay mockup.

3.3 Analyses

The structural modules were analyzed to verify that the selected system parameters were commensurate with requirements for space application. Finite-element analysis was used to determine stiffness and system natural frequencies. An analysis of the double-fold module nodal joints was performed to determine stability under load.

3.4 Testing

The test articles were delivered to MSFC on schedule. Vought personnel assisted in both installation in the Neutral Buoyancy Simulator (NBS) and the actual testing.

The tests were distinguished by being the first to make use of the newly installed Remote Manipulator System (RMS) simulator.

Nineteen tests were planned. However, four were deleted due to limitations of tank size or RMS sensitivity. Fifteen were accomplished and recorded on video tape for later analysis. All operations went well with no significant surprises. Need for a few changes/improvements were noted and are included in the recommendations. An independent "Quick Look" report is included as Appendix I of this report.

3.5 Automatic Deployment Study

An additional effort was undertaken to determine the feasibility of automatic deployment of space structure.

First a literature search was made for other deployable structures to provide a data base of deployment techniques, then the Vought Contract developed DFDC and the Vought IR&D developed Biaxial Scissors Fold Concept (BASF) were studied for feasibility of automatic deployment.

Several automated concepts were generated and studied for practicality. Two were submitted to MSFC for selection of a candidate for further work. A spring deployed version of the DFDC was chosen to be carried into preliminary design as the final part of this contract.

3.6 Preliminary Automatic Deployment Design

The deployment mechanism developed is a cable system powered by a long, small diameter helical spring loaded in compression, being essentially fail-safe. The springs are located inside structural members for additional protection. Accessory arms are required to initiate deployment. The geometry is such that the opening moment is increased faster than the spring loading decreases, thereby assuring full deployment. Restraint during deployment is provided by a clock-work cable reel governor, or equivalent, to protect the structure from opening shock.

During the study it was also determined that it would be practical to retract the structure by incorporating a motor drive with the cable reel governor.

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4.0 TEST HARDWARE DESIGN

This section describes and discusses the neutral buoyancy test hardware. The primary elements were:

- o Double fold double-cell modules (2 ea)
- o Interconnect, consisting of:
  - "Card Table" (folding) legs (3 ea)
  - Loose members (2 ea)
- o Stowage Fixture (1 ea)
  - Designed for reconfiguring 4 ways
- o Base frame (1 ea)
  - Designed to support deployed modules

The design drivers for NBS test components were cost, flexibility of test operations, compatibility with desired test parameters, assured neutral buoyancy and corrosion protection.

4.1 Neutral Buoyancy

It was decided at the outset of the design effort that hard, sealed buoyancy chambers would be the most reliable and would avoid later complications and schedule problems. Positive buoyancy was designed into or around the structure by calculation, so that small unobtrusive weights could be used for final trim.

External flotation collars were used on the small diameter verticals, laterals and the outside portions of the telescoping diagonals. These consisted simply of concentric aluminum tubes with the intervening space sealed. This permitted initial balancing of the individual members in water before final location of the float devices. The folded envelope was slightly compromised in this design compared to the basic flight design envelope. The larger diameter longitudinal members were used to establish the folding geometry. Internal float chambers were created by either sealing plugs directly into the members or installing a separate sealed tube section. As with the external floats, this permitted initial flotation balancing. Flotation for the joints and accessories was provided for in the strut design.

Initial neutral buoyancy was established on a member by member basis in the fabrication area using a specially constructed tank. This resulted in a minimum of final trimming when installed in the NBS facility.

The flotation collars were painted blue to differentiate easily the parts of the hardware that were not related to the flight design.

4.2 Corrosion Protection

One of the auto lock couplers, fabricated under the Phase I of the contract, was chosen to test the adequacy of a minimal corrosion protection system. This part was chosen because it represented the aluminum and stainless steel materials to be used. Also, due to the number of close tolerance moving parts it could not be elaborately protected by primers and paint. After submersion in a local chlorinated pool with an environment similar to the NBS for three weeks, it was still operable and without serious deterioration.

Therefore, it was determined that no finish on stainless materials would be required except for dry lube on moving parts, and that anodize would adequately protect the aluminum. However, for better appearance and further protection, the majority of the structure was protected with either alodine or anodize as a base, adding primer and finishing off with an epoxy paint.

4.3 Cost Considerations

Although a flight design may be made mostly of graphite-epoxy, aluminum was chosen as the basic material for the test article due to ready availability and cost.

The node fittings were simply profiled from plate and joined with screws to fully represent typical flight hardware form and function.

The support structure was an extemely simplified cradle which did not include the additional support points and strength which would be required for launch environment.

Rigid detachable struts, or equivalent, built on to the modules for folded positioning and to sustain launch loads will be a flight requirement, but were not used on the test article.

The base frame, representing a spacecraft docked for a structural add-on, was a "boiler plate" design. Heavy aluminum channel was fabricated into a simple picture frame, locating the four points of attachment for the deployed DFDC.

4.4 Hardware Description

Figure 4-1 shows all the hardware installed in the Orbiter Payload Bay mockup at the NASA MSFC Neutral Buoyancy Simulator Facility.

Figure 4-2 is a schematic representation of the test structure erected in the NBS orbiter payload bay mockup. The full 15 meter arm consists of two 6 m modules connected by a 3 m module-to-module interconnect. Alternatively, modules can be deployed and erected independently, or two modules with the interconnect can be sequentially deployed and erected, or two initially connected modules can be deployed as a unit.

4.4.1 Modules

The basic structural concept is a cube which folds in two directions for minimum volume stowage. In order to include all folding characteristics of an extended structure it was necessary to use at least a two cube module, hence the double-fold double-cell (DFDC) nomenclature. This structure may be extended in any combination of X, Y, or Z axes as desired for beam or platform.

With this particular point design, electrical utilities may be added with no increase in stowed volume. A module complete with flotation collars is represented in Figure 4-3.

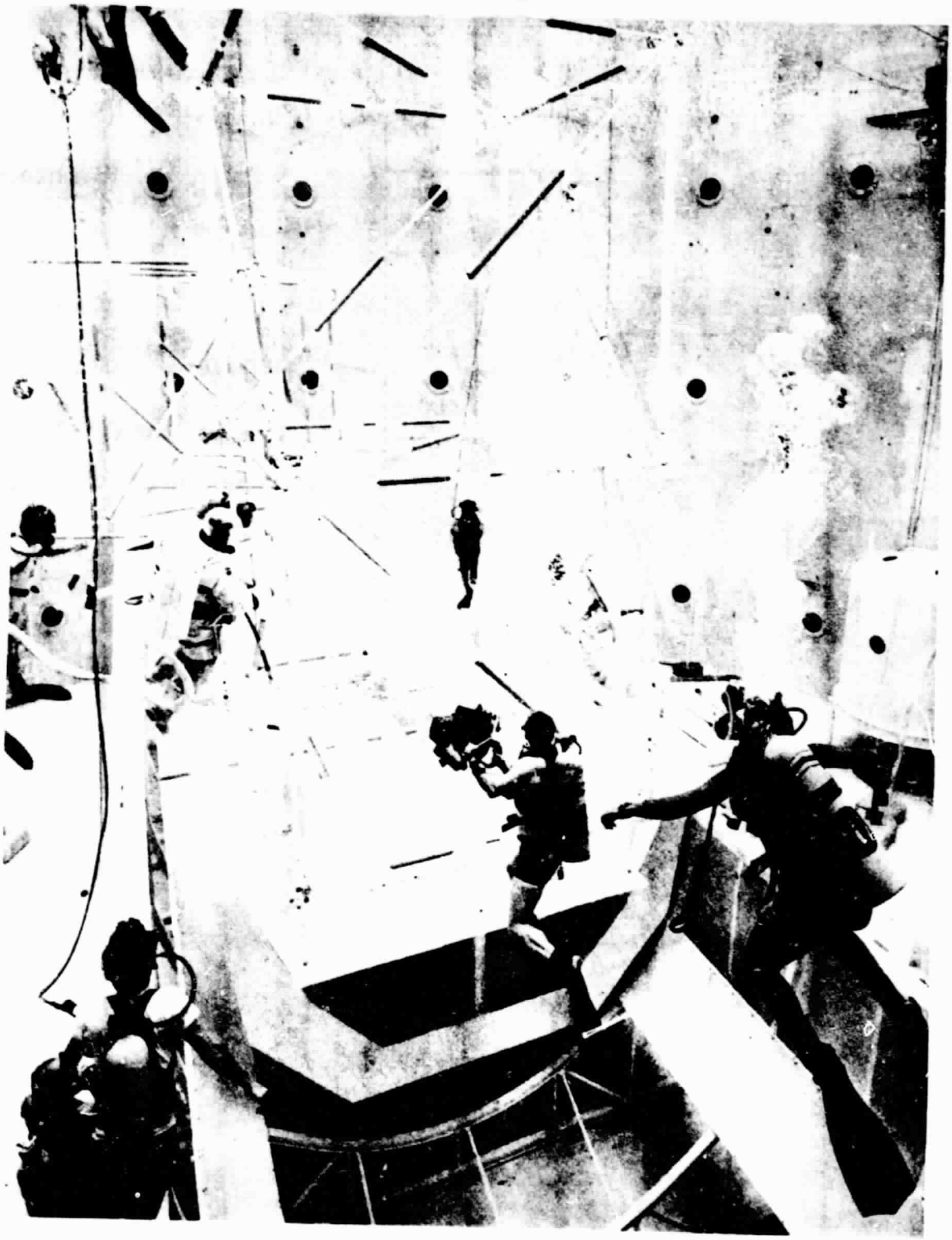

Figure 4-1 NBS TEST INSTALLATION

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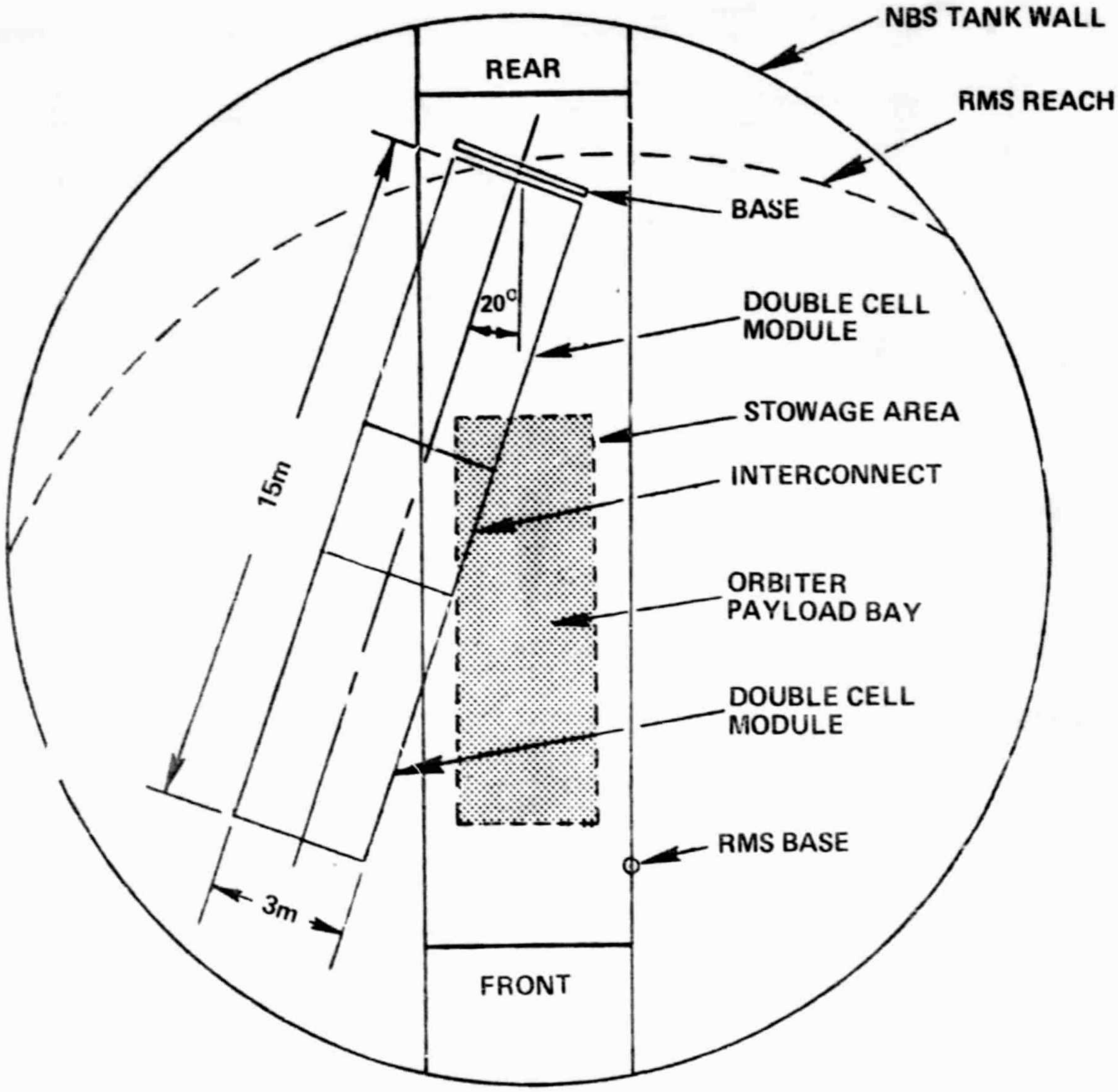

Figure 4-2 TEST LAYOUT IN NEUTRAL BUOYANCY SIMULATOR

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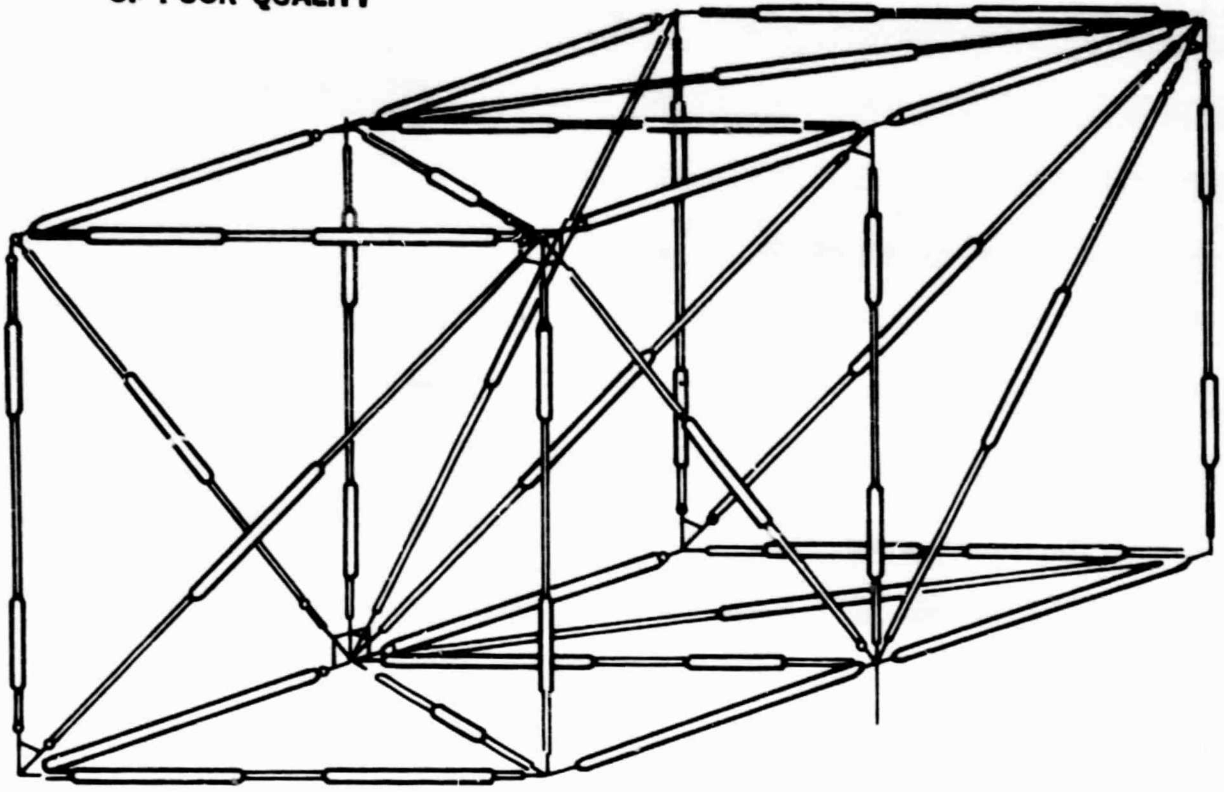

Figure 4-3 DOUBLE-FOLD DOUBLE CELL MODULE

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The basic elements in the structure are the tubular struts which were sized (See Section 5) to simulate a section of a 1979 Science and Applications Space Platform (SASP) arm (Ref. 7). Figure 4-4 shows a strut with a typical end fitting which permits adjustment at assembly. A combination of coarse and fine threads, both right hand, at opposite ends of the strut permit infinite turnbuckle-like adjustments without the possibility of separating.

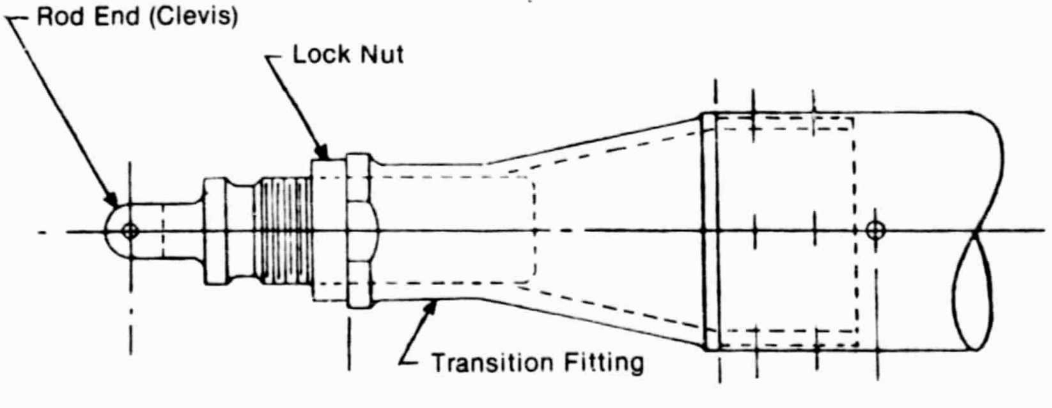

Figure 4-4 STRUT

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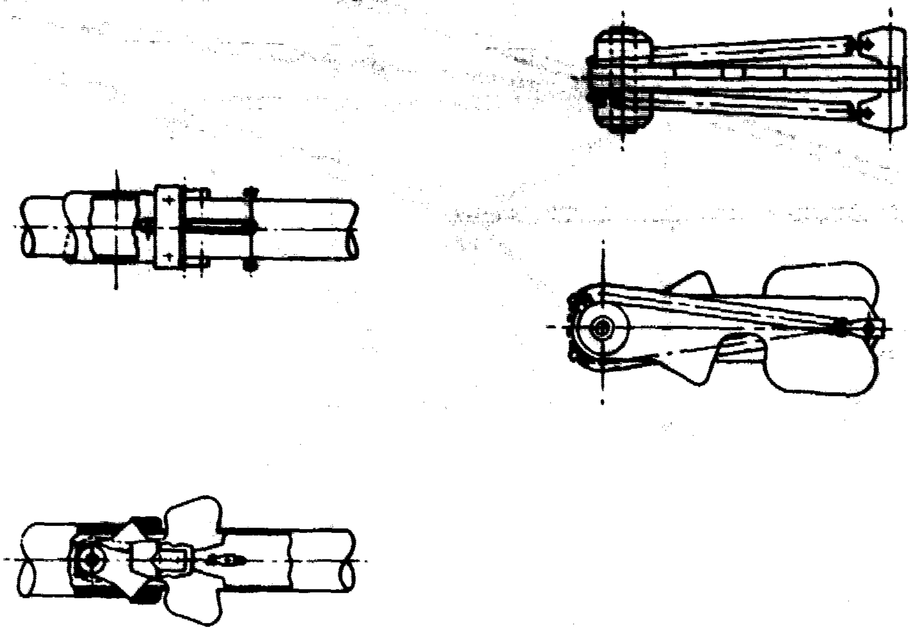

Figure 4-5 TELESCOPE LOCKS

The other significant strut feature is shown in Figure 4-5. The diagonals which telescope must, of course, lock in the deployed configuration. During deployment the mechanism automatically locks the diagonals when fully contracted. This is accomplished by the ramping of the two spring-loaded levers onto the collar riveted to the end of the outer tube. Extension loads are taken by the lever ramps while compression loads are taken by stops on the inner tube. The wedging action of the levers against the collars provides a no-free-play connection. The ears on the levers extend outward in the locked position, providing an indication that the diagonal is locked. To unlock the diagonals for folding, the mechanism is released and held in the unlocked position by the simple one-handed operation of compressing the lever ears. The device remains in this position until rearmed by sliding the spring-loaded wedge backward, thus allowing the levers to spring out.

The nodal elements of the DFDC are represented in Figure 4-6. The lug/clevis arrangement was widened (from the Phase I design) and roll pins were used as a result of the studies in Ref. (1) and (2). The wider lugs provide greater axial stability for the strut connection and the roll pin provides greater stability by removing free-play (non-linearity) from the joint. The basic node structure is not weight optimized but represents functionally the load paths and the proper spacing of the struts for folding. In addition, the module connector mount is incorporated onto the node fitting to achieve intersecting load paths to the greatest possible degree.

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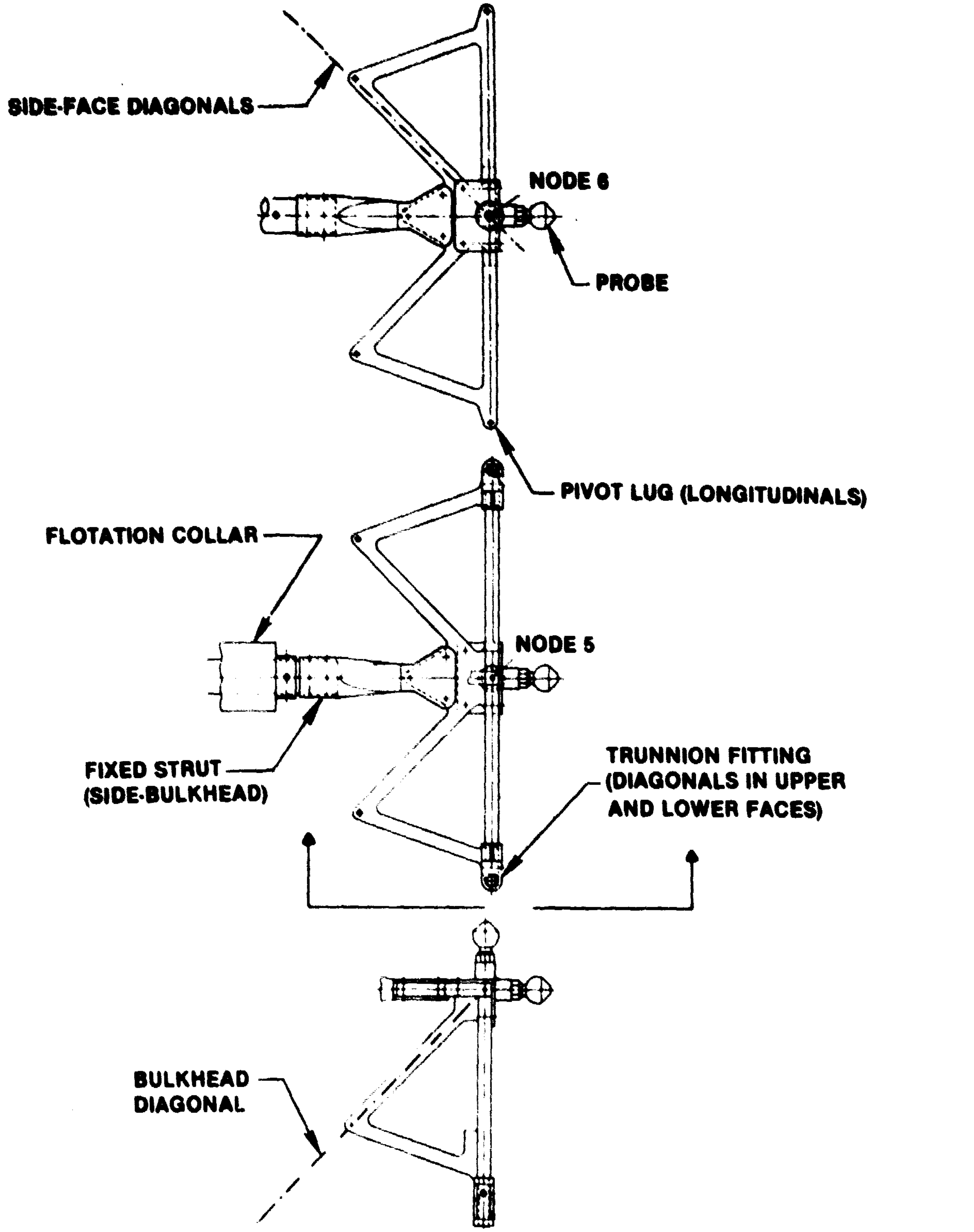


Figure 4-6 NODE FITTINGS

The single-fold configuration offers a moderate packaging density, but a module designed only for single-fold stowage requires fewer telescoping diagonals and can use simpler joints than the double-fold configuration. The double-fold configuration requires every diagonal member to telescope, but much better packaging density is achieved. For the double-cell neutral buoyancy modules, the deployed volume to folded volume ratio is 5.1/1 for single-fold and 28.7/1 for double-fold. Longitudinal members were 6.35 cm O.D. with 0.089 cm wall thickness. Lateral members had 3.175 cm O.D. and 0.159 cm wall thickness. To allow telescoping, diagonal members were made with an inner and outer tube, the outer tube being 3.81 cm O.D. with 0.125 cm wall thickness and the inner tube being 3.175 cm O.D. with 0.159 cm wall thickness. To minimize sliding friction in the telescoping diagonals, teflon bearing pads were used between the inner and outer tubes. The folding of a double-fold module requires each of the diagonal struts to telescope (extend), whereas in the deployed configuration, the concentric tubes must be locked together in the contracted configuration to carry axial loads.

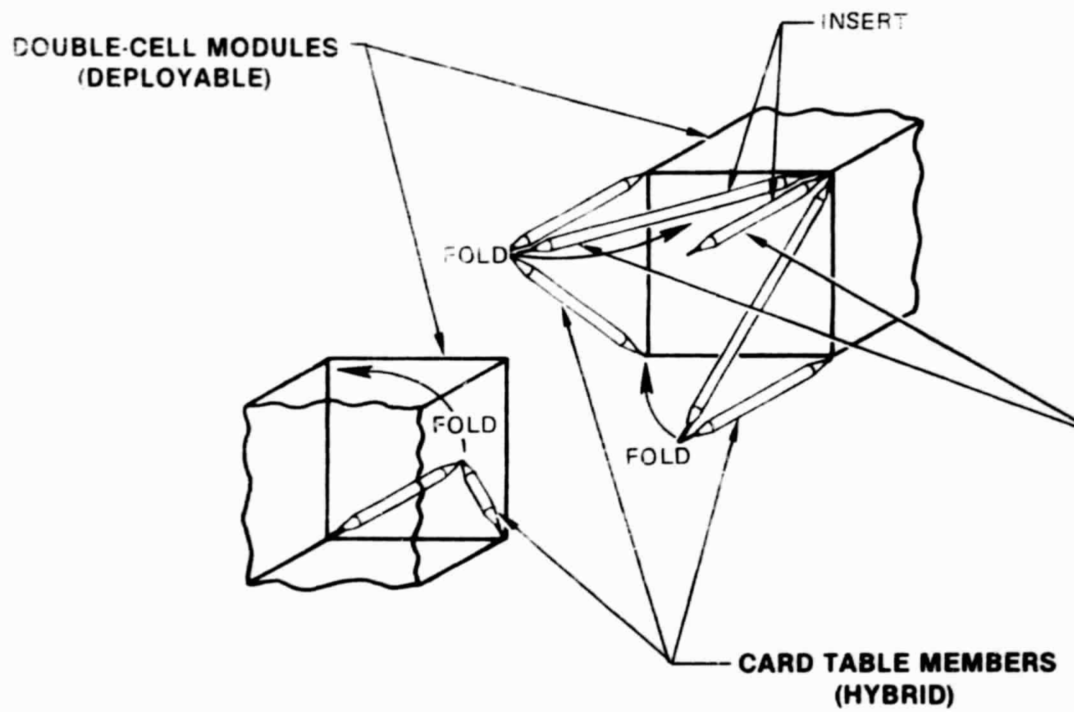
4.4.2 Module-to-Module Interconnect

If the basic modules are joined directly, redundant vertical and lateral members will exist at the connection plane. A module-to-module interconnect is a special structural system used in this case to eliminate this redundancy. Several configurations are possible, including separate folding structures, folding legs pre-attached to the modules, and a collection of loose members. For the NBS tests, an interconnect consisting of a combination of folding "cardtable" legs and loose members was chosen for evaluation and testing. This arrangement allows assessment of both member deployment and loose member assembly operations to add to the study data base.

As indicated in Figure 4-7, two cardtable legs, each comprising a longitudinal and a diagonal member, were attached to one module, and one cardtable leg was attached to the other module. The remaining longitudinal and diagonal struts were separate loose members. For tests requiring interconnect assembly, the cardtable legs fold against the modules in a single-fold stowage configuration. During deployment, the cardtable legs unfold and connect to the other module by means of a module-to-module coupler (Figure 4-8). Each of the cardtable legs was provided with a spring-loaded folding stabilizer strut that holds the unfolded leg in position for module connection. Loose members may then be inserted using the automatic coupler clevis shown in Figure 4-9.

4.4.3 Payload Bay Support Fixture

For the neutral buoyancy tests, a payload bay support fixture was designed and built. The purpose of this device was to simulate the type of stowage rack required for flight so that procedures for unstowing and stowing the structure could be evaluated and timelines established. The support fixture consisted of a subframe mounted on a payload bay pallet and a modular system of uprights with retractable cups (or probes as needed) for engaging the coupler probes (or drogues) on the folded test structure. These retractable cups and probes were actuated by EVA subjects through a system of pushrods and cranks.



TWO ADDITIONAL CONCEPTS REPRESENTED

- **"Card Table"**
- **Single Members**

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Figure 4-7 MODULE INTERCONNECT

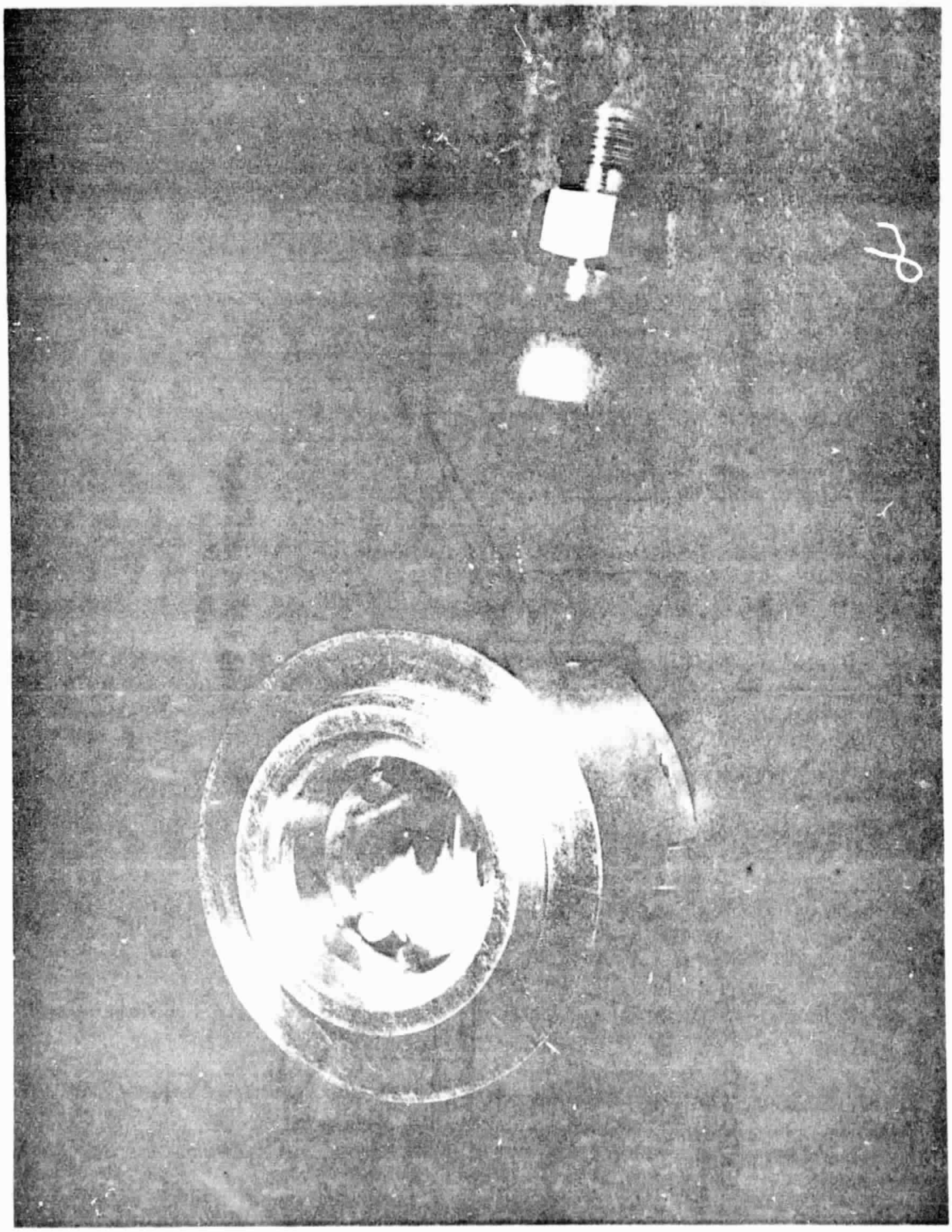

Figure 4-8 MODULE TO MODULE COUPLER

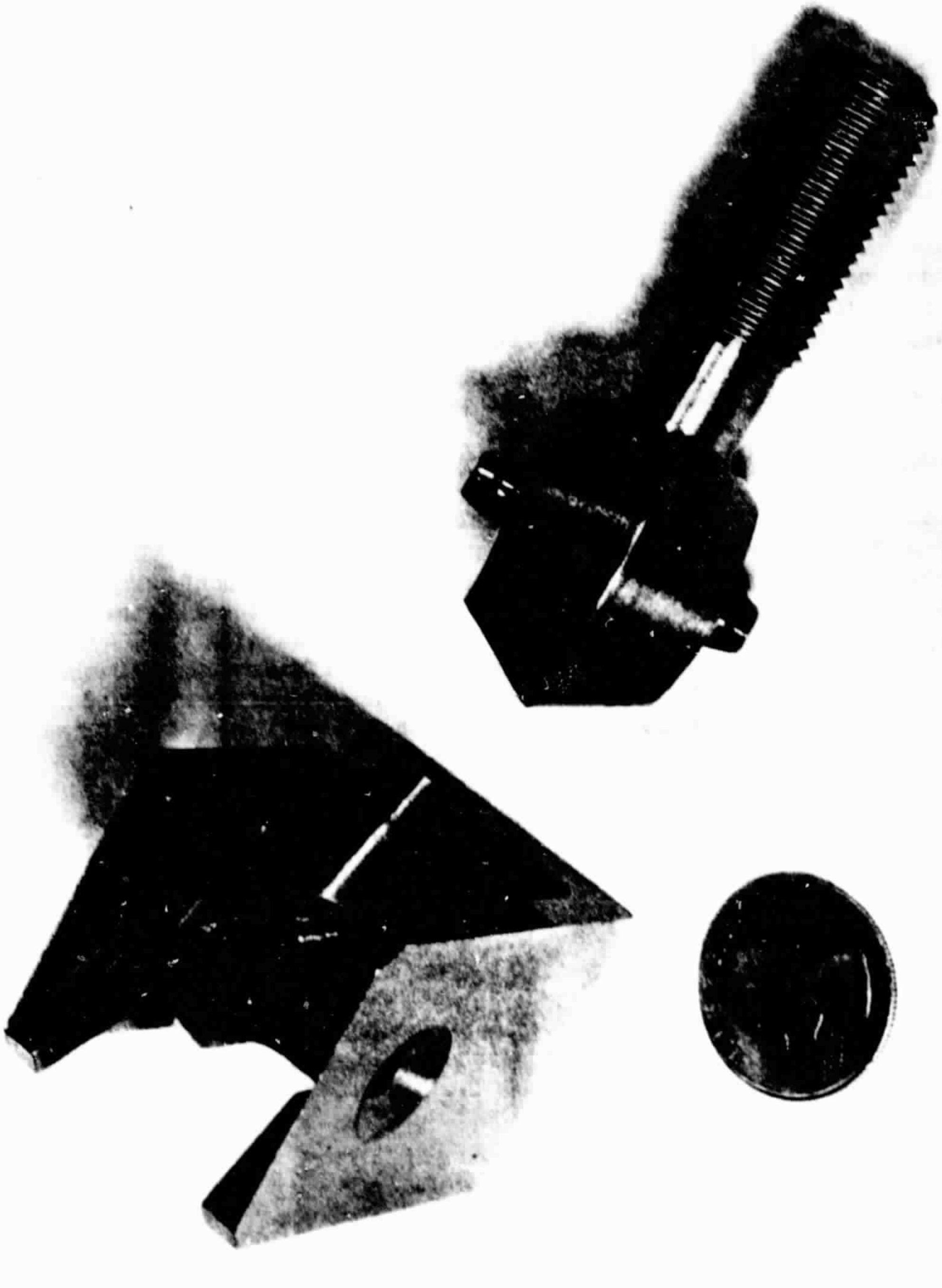

Figure 4-9 AUTOMATIC COUPLER CLEVIS

Figure 4-10 illustrates how the fixture was configured to provide desired initial stowage conditions. By changing the arrangement of support towers, it was possible to stow two double-cell modules in the following configurations:

(1) Two unattached single-fold modules.
(2) Two unattached double-fold modules.
(3) Two initially connected single-fold modules.
(4) Two initially connected double-fold modules.
(5) Two unattached single-fold modules with folded cardtable legs.

The latching mechanism of the support fixture was operated from two work stations, one on each side of the payload bay. To unstow each double-cell module required an EVA subject at each work station to pull two tee handles, each of which released two couplers. Following the coupler release, the module could then be lifted from the support fixture by the RMS. Restowing a module required reversal of this operation. The folded module was first brought into position in the support fixture, the coupler probes or drogues on each side were aligned with the corresponding cups or probes on the support fixture, and the tee handles were pushed in to engage the couplers.

4.4.4 Base Support Frame

To provide a point of attachment for constructing the test structure, a base support frame was designed and fabricated. This structure, shown in Figure 4-11, consisted of a 3 m square frame supported by legs bolted to the payload bay mockup longerons. The primary structural material used in the construction was 20.32 cm (8-inch) channel section 6061-T6 aluminum alloy. The structural modules were attached to the base frame at the corners by means of module-to-module couplers with the probes mounted on the base frame. The base frame was located at the aft end of the payload bay mockup with its normal axis angled at 20 degrees to the starboard of the Orbiter centerline. This configuration was based on tradeoffs between fidelity to likely flight construction geometry, the need for the assembled structure to remain within the RMS arm manipulating envelope, boundaries established by the NBS tank walls and water surface, and the need to leave the stowage area unobstructed by the first module deployed.

4.4.5 Connect Fittings

The module-to-module auto lock coupler, Figure 4-12, had a broad range of applications and excellent operational characteristics. The main purpose of the coupler was to join two structural modules. However, it was also generally applicable as an end connector for single members and for mounting experiment carriers or other packages on platforms. Use as a module coupler for cubic modules required four couplings to be made nominally in a plane. This required a soft capture capability and operability within misalignment tolerances. The coupler would soft capture with a ten degree angular misalignment, a 12.5 mm radial mismatch, or 2.5 mm axial engagement variation. The probe was captured by the drogue fingers 2.5 mm before bottoming out. Once captured, the probes could not back out of the drogue without operation of the release mechanism. An advantageous feature of this coupler is that, once bottomed out, there is essentially no axial free play and the force/deflection relationship is linear. This was verified in the Phase I program by static and vibration tests.

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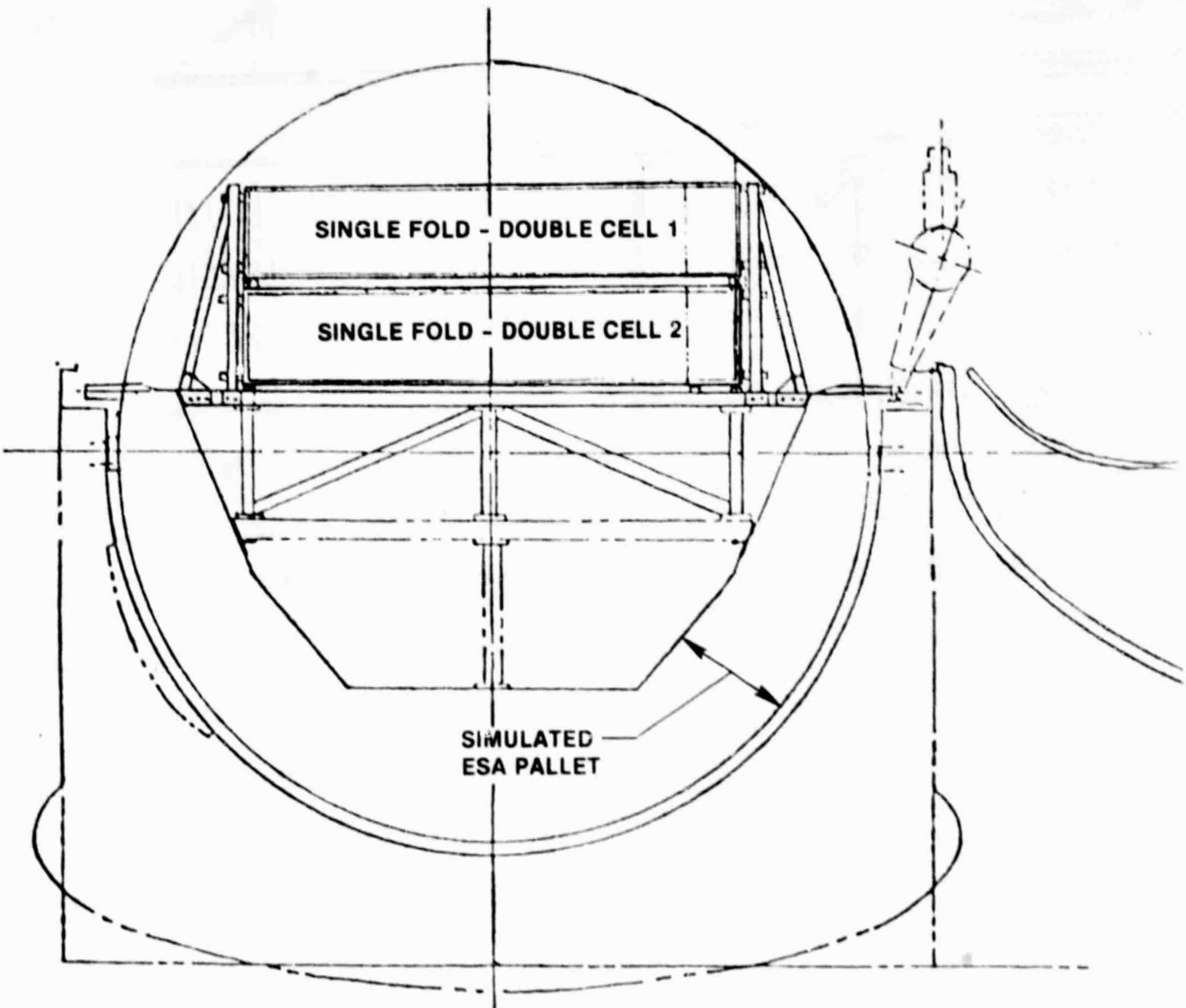

Figure 4-10 STOWED SINGLE-FOLD MODULES

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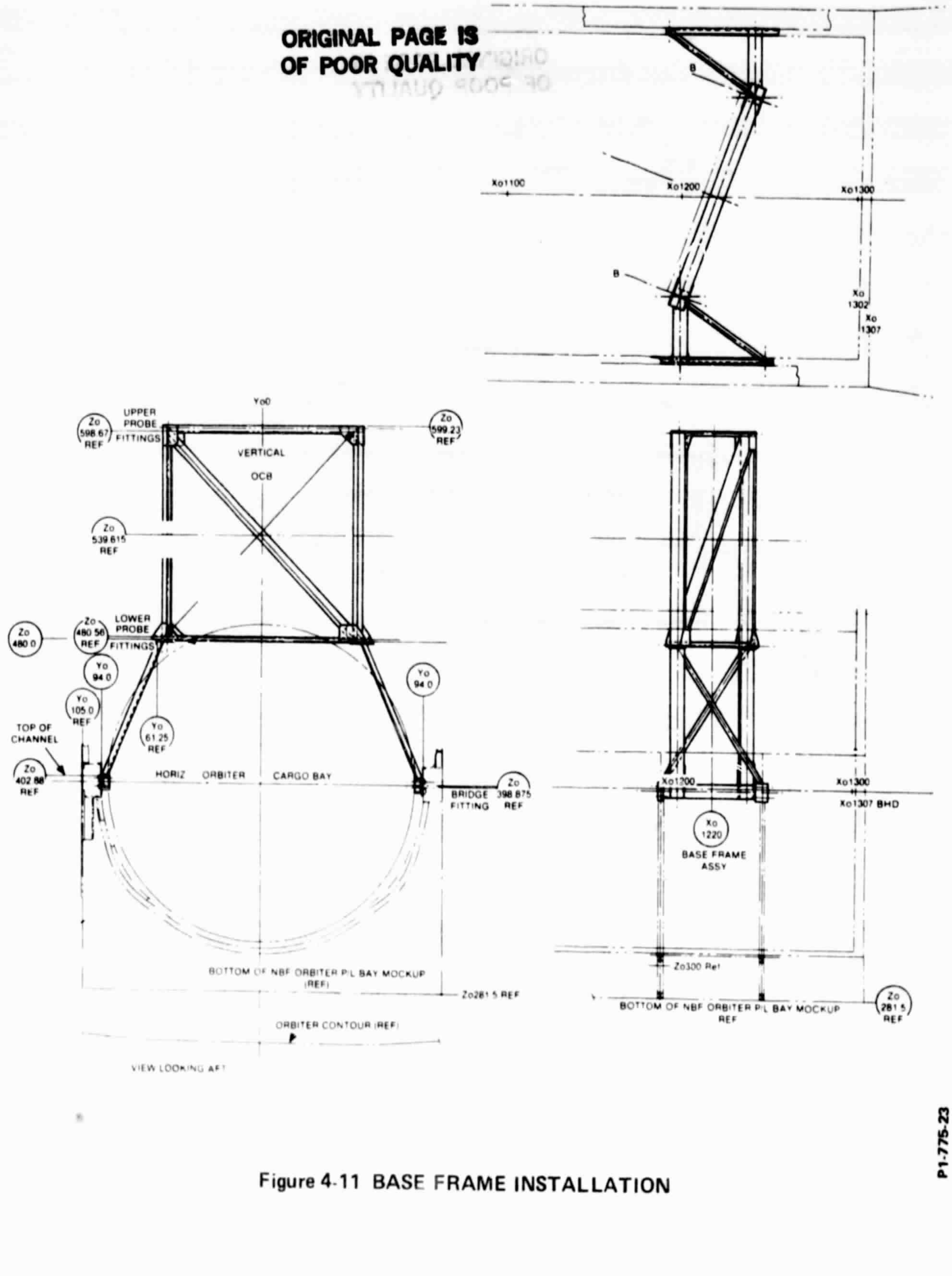

Figure 4-11 BASE FRAME INSTALLATION

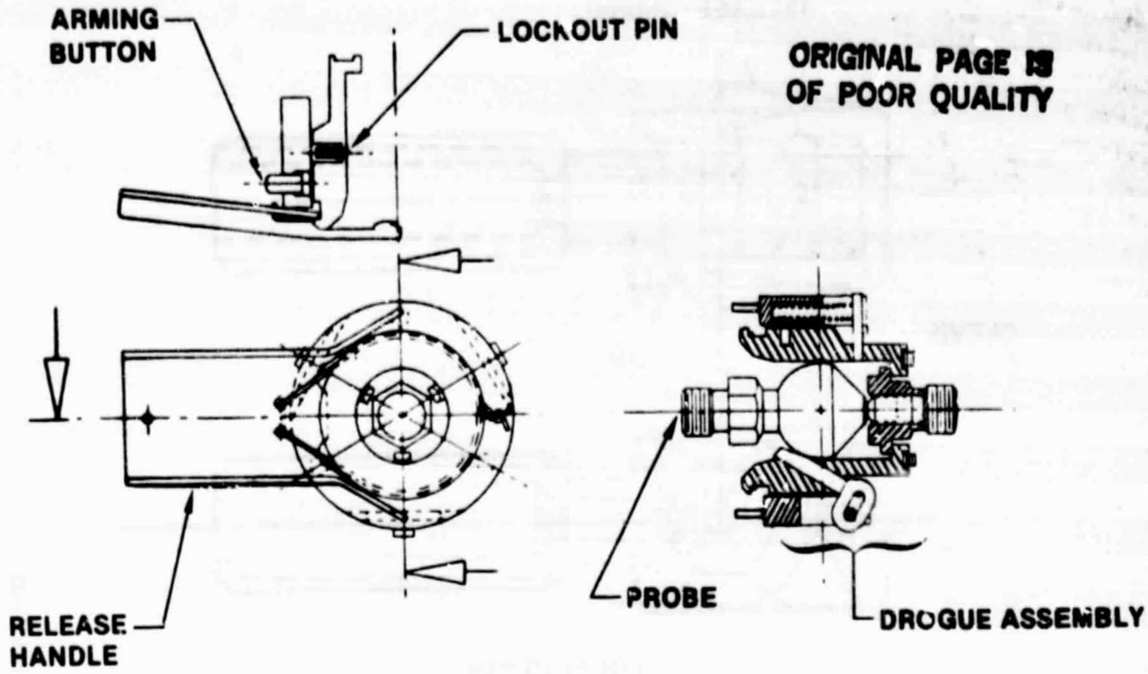

Figure 4-12 AUTO-LOCK COUPLER

One deficiency of the Phase I design pertained to the release of the coupler. To break the connection, the drogue collar had to be moved backward to retract the holding pins. To release four couplers simultaneously, as required to disconnect two modules, required all four collars to be held in the release position. The redesigned coupler has a spring-loaded device for achieving this. Once released, the coupler remained in the release position until armed again by manually pressing a button on the side of the collar. To aid a suited EVA subject in retracting the release collar, a lever was added to the coupler as shown. For the neutral buoyancy hardware, this lever was a single sheet metal part wired in place on the collar. As noted in Section 6.3 this wire presented a small safety hazard, and was therefore removed, causing difficulty during the test.

The second joint type used in the neutral buoyancy testing was the automatic coupler clevis, Figure 4-13. This fitting was used to make connections on the ends of the single member struts in the module-to-module interconnect. It features end or side insertion capability in a 180-degree arc with a $\pm$ 12.5 mm gathering range.

To release this coupler required retraction of the spring-loaded tapered pins. A simple spring clip was designed for attachment to the clevis to allow this to be easily accomplished. Compressing the spring sides with one hand causes a small tab on each side of the clevis to push the hinge pins inward, releasing the connection. The parts are separated with the other hand

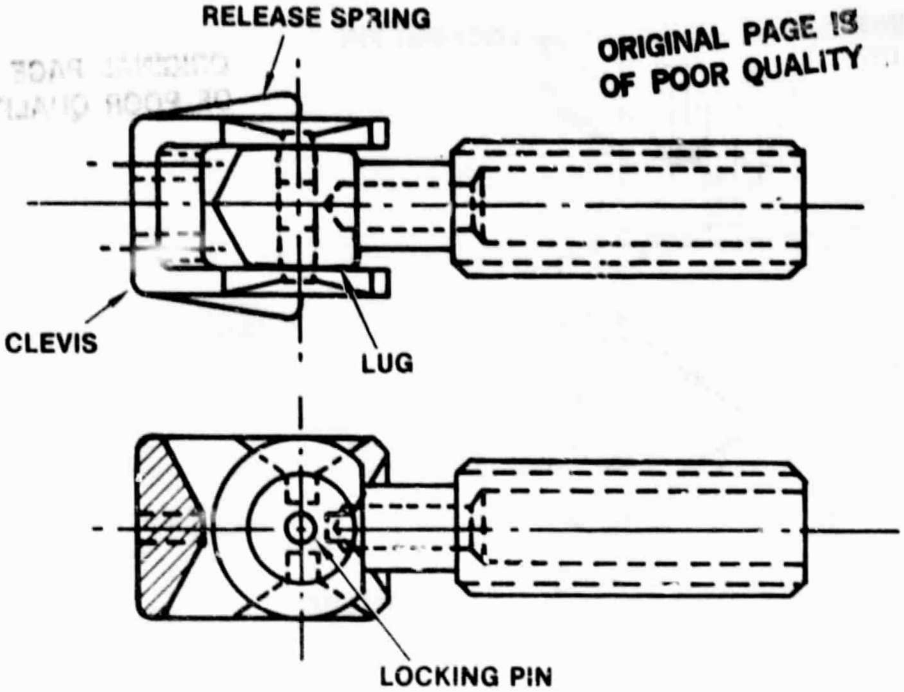

Figure 4-13 AUTOMATIC COUPLER CLEVIS

while the release spring is compressed. Although the disconnection is thus a two hand operation, the simplicity of the design was judged to outweigh the advantages of a one-hand release which would require a more complex internal mechanism in the lug.

4.4.6 Electrical Utilities

MSFC determined that electrical power and signal wire routing requirements for a 25 kw SASP type structural arm would be:

- 8 each 1/0 power cables
- 4 each #8 AWG wires
- 8 each #12 AWG wires
- 40 each twisted shielded pairs #20
- 8 each coax

The problem associated with installing utilities on a folded structure was established by Vought to be the routing of the cables across folding joints (nodes), such that packaging volume and wire flexing forces would not unduly affect the deployable concept. In addition it was assumed that all services should be available to all faces of the arm so there would be no limitation to experiment placement.

Since the four nodes at the center bulkhead of the DFDC are repetitive throughout an extended arm, demonstration of packaging and flexing effects was accomplished by installing wire bundles at these points on one DFDC module. Figure 4-14 shows the arrangement of power and signal wires. Figure 4-15 shows a typcial routing arrangement which permits folding of the structure.

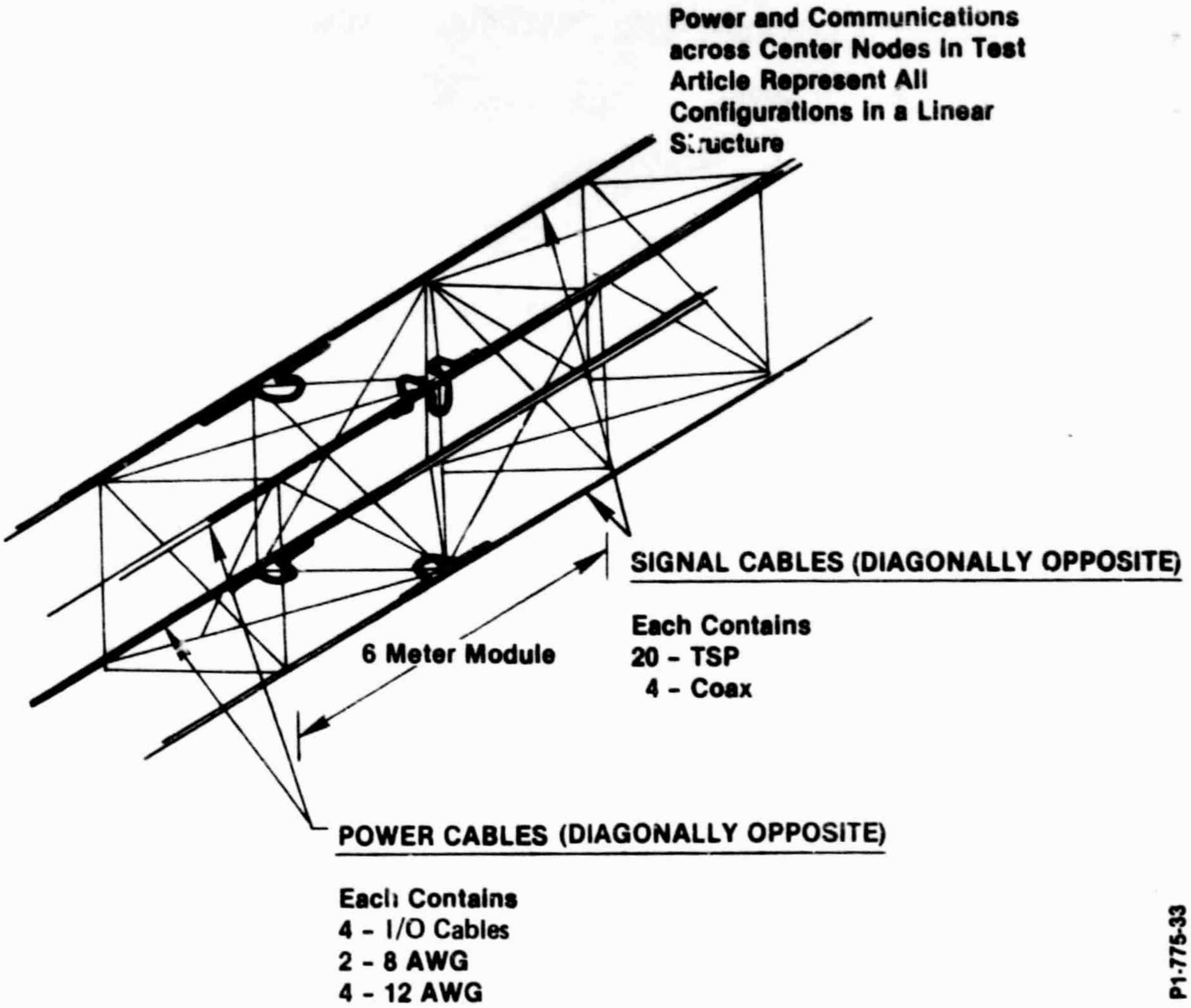

Figure 4-14 ELECTRICAL UTILITIES ROUTING

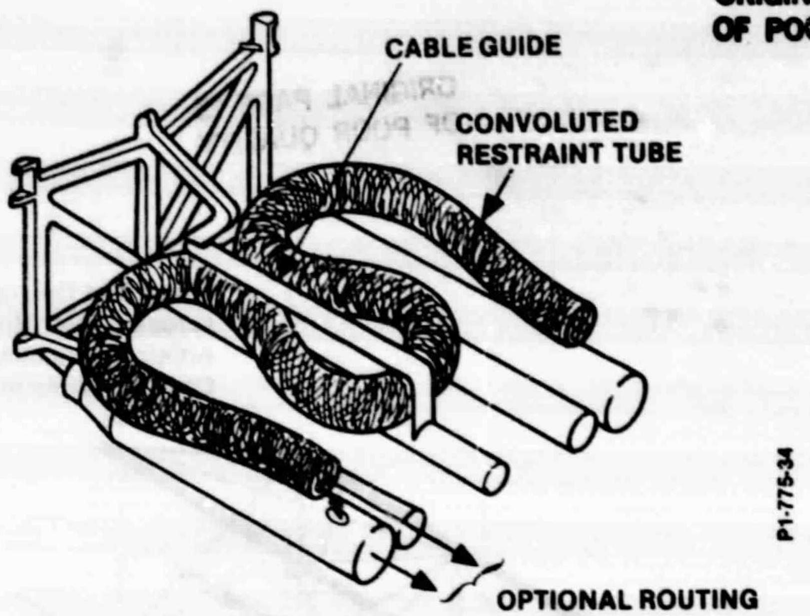

Figure 4-15 TYPICAL NODE CROSSING (FOLDED)

Neither connectors nor node to node routing were addressed in this study. However, it may be noted for this point design, the wire could be routed either inside or outside the longitudinal members between nodes.

The study determined that wire bundle flexibility is primarily established by three criteria; wire size, bundle looseness and insulation properties. The 1/0 guage power wires promised to be the most difficult to manage. However, for demonstration purposes it was found that commercial welding cable was ideal, having a small strand loosely bound wire bundle with soft insulation. Individually the smaller signal wires were relatively flexible in standard aerospace grades. Thus, the remaining problem was that of making up a node crossover wire bundle that would be loose enough to permit the wires to bend individually rather than as a unit when tightly bound together as is usual with typcial string tie or braided support.

The final demonstration installation is shown in Figure 4-16. Wire support and control is provided by a convoluted conduit which may be considered as having the additional advantage of providing micrometeroid protection.

It was possible with this point design DFDC to cross all nodes with the required utilities without affecting stowed volume.

With the four demonstration wire bundles installed, the DFDC module was operated in the "zero-G" environment of the MSFC Neutral Buoyancy Simulator. Doing the same stowage/deployment maneuvers, no detectable effects were felt with the wire bundles added.

Neutral Buoyancy for the cabling was accomplished by adding sealed aluminum float chambers in the same manner as for the basic structure.

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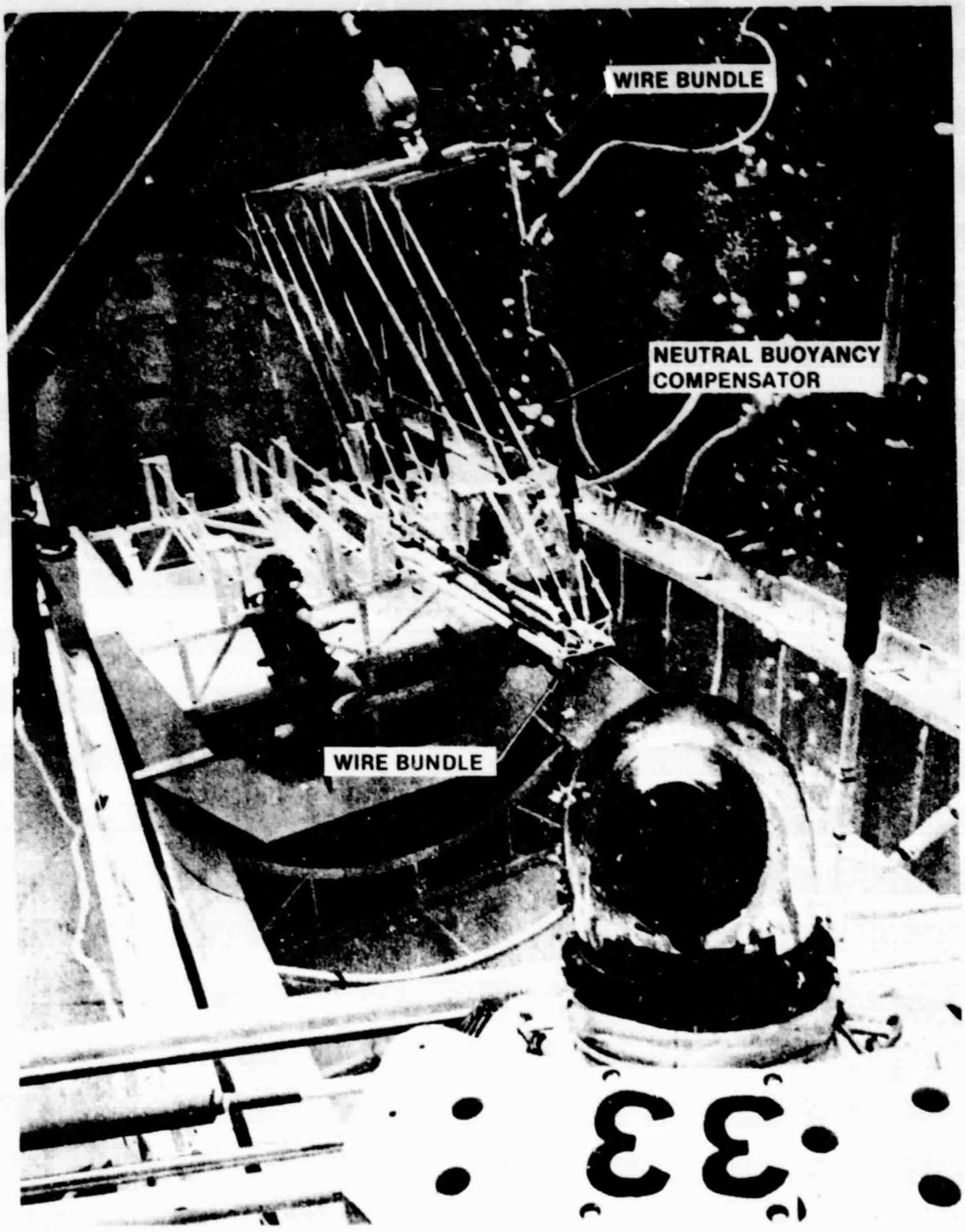

Figure 4-16 MODULE INSTALLATION WITH WIRE BUNDLES

5.0 STRUCTURAL ANALYSIS

This section presents a static and dynamic analysis of an 18 m-long aluminum truss strong back (arm) configuration made up of a six-cell, double-fold module. The analysis is essentially the same as the structural analysis presented for the Phase I baseline structure of Ref. (1), except for the substitution of member sizes (noted below) on the neutral buoyancy test hardware. That sizing was based on the Science and Application Space Platform (SASP) requirements of Reference (7). The purpose of this analysis was to compare performance of the test structure with the previous baseline and to verify that the test hardware meets reasonable criteria for strength, stiffness, and natural frequency. It is recognized that different applications will require specific tailoring of member lengths, diameters, and wall thicknesses, as well as material. For structures requiring high dimensional stability, for example, use of a low coefficient of thermal expansion material such as graphite/epoxy would probably be used.

5.1 Finite Element Model

A finite-element model composed of tubular axial elements (Figure 5-1) was used in the analysis. As in the Phase I analysis, three payload masses of 3040 kg each were assumed attached to the arm, and the arm was assumed to be rigidly attached at the base. These payload masses were distributed as concentrated masses at twelve joints, namely; the four corners at the free end, six meters from the free end, and twelve meters from the free end. The mass loading shown in Figure 5-2 is representative of typical SASP loading per Ref. (7). Joint masses were assumed to be 0.79 kg each. The essential difference between the Phase II truss model and the Phase I baseline model is the substitution of 0.089 cm wall thickness longerons in place of the 0.318 cm thickness. In both cases, the diagonal and bulkhead member sizes were assumed the same. Material parameters for 6061-T6 aluminum were used.

5.2 Static Analysis

Maximum allowable loads in the diagonal members were established, based on critical buckling for pin-ended columns. From the computed loads, it was determined that a transverse acceleration of 0.0079 g would provide a zero margin in the critically loaded diagonal. This compares with 0.0092 for the Phase I baseline and is well above the estimated Low Earth Orbit (LEO) operational loading environment of 10^{-4} or 10^{-5} g of Ref. (7). The critical loading condition and results are shown in Figure 5-2. The resulting tip deflection is 0.008 m compared with 0.0036 m for the Phase I baseline.

Stiffness was calculated for the 15 meter test structure (see Section 5.5) to be 0.0011 cm/N (0.002 in/lb). Measured stiffness was noticeably lower, measuring 0.0017 cm/N (0.003 in/lb) after correcting for wall deflection. Hysteresis quite possibly is a significant contributor to this delta (see Section 5.6). However, to understand the full implications, including joint rotation (see Section 5.4), further investigation seems warranted.

5.3 Modal Analysis

The first four natural modes of vibration are shown in Figures 5-3 through 5-6. Modes one and two, in order of increasing frequency, are "first" bending modes in diagonal planes and occur at 0.55 and 0.56 Hz. Mode three is

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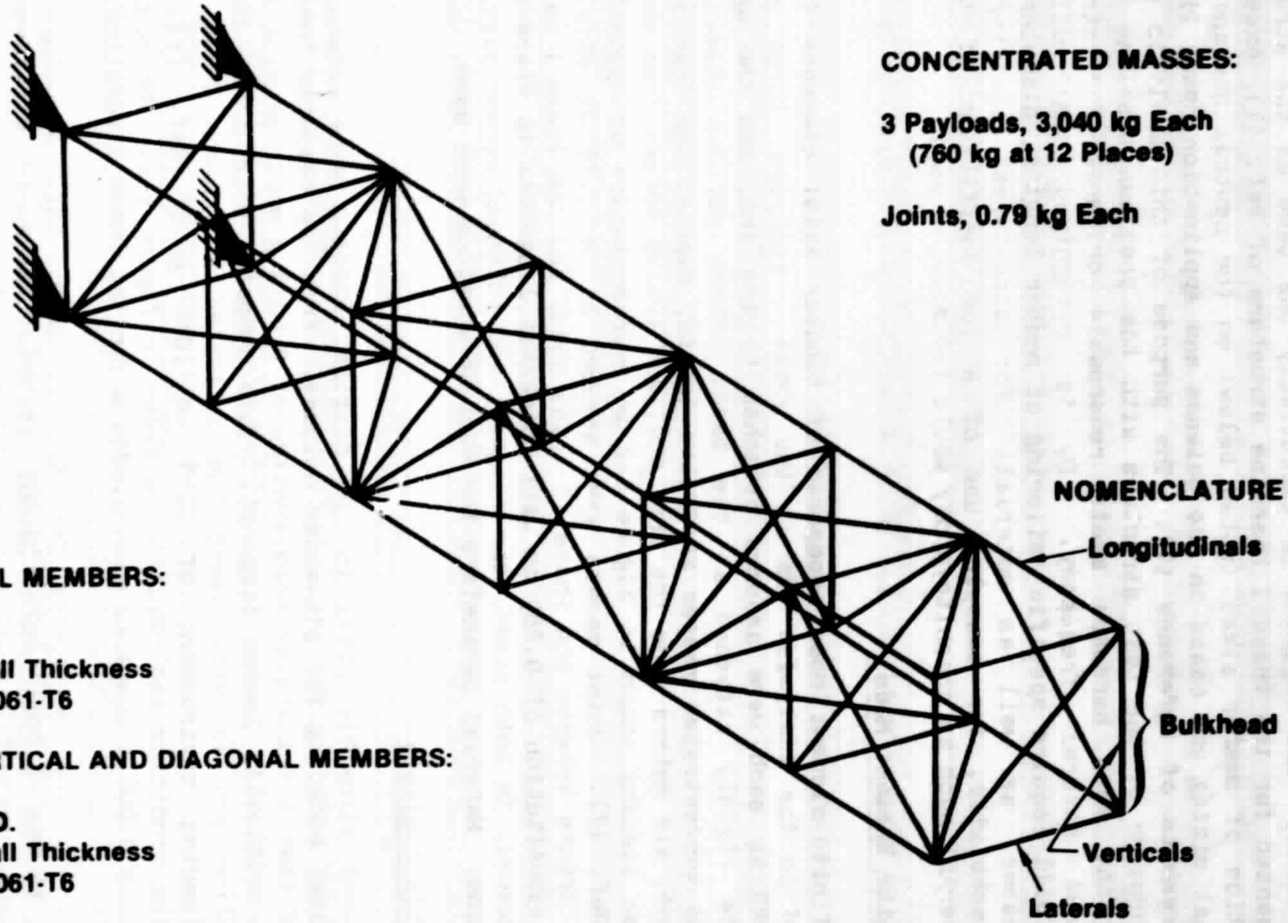
CONCENTRATED MASSES:

3 Payloads, 3,040 kg Each
(760 kg at 12 Places)

Joints, 0.79 kg Each



LONGITUDINAL MEMBERS:

6.35 cm O.D.
0.089 cm Wall Thickness
Aluminum 6061-T6

LATERAL, VERTICAL AND DIAGONAL MEMBERS:

3.175 cm O.D.
0.159 cm Wall Thickness
Aluminum 6061-T6

Figure 5-1 SIX-CELL, 18-METER TRUSS STRUCTURAL MODEL

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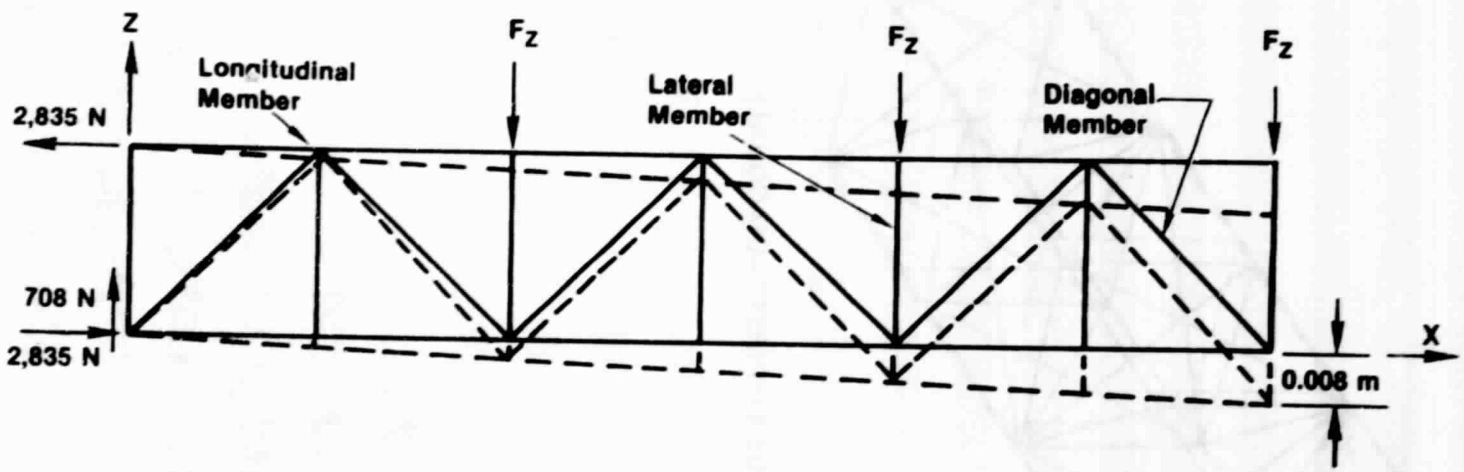

MAXIMUM LOADS

MEMBER	ALLOWABLE	COMPUTED
Longitudinal	6,481 N	1,454 N
Lateral	1,297 N	187 N
Diagonal	648 N	648 N

$P = 29{,}822$ N
(Payload Weight)

$A_Z = 0.0079\,g$

$F_Z = PA_Z$

$= 235$ N

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Figure 5-2 STATIC REACTIONS AND DISPLACEMENTS FOR EXPANDABLE TRUSS MODEL

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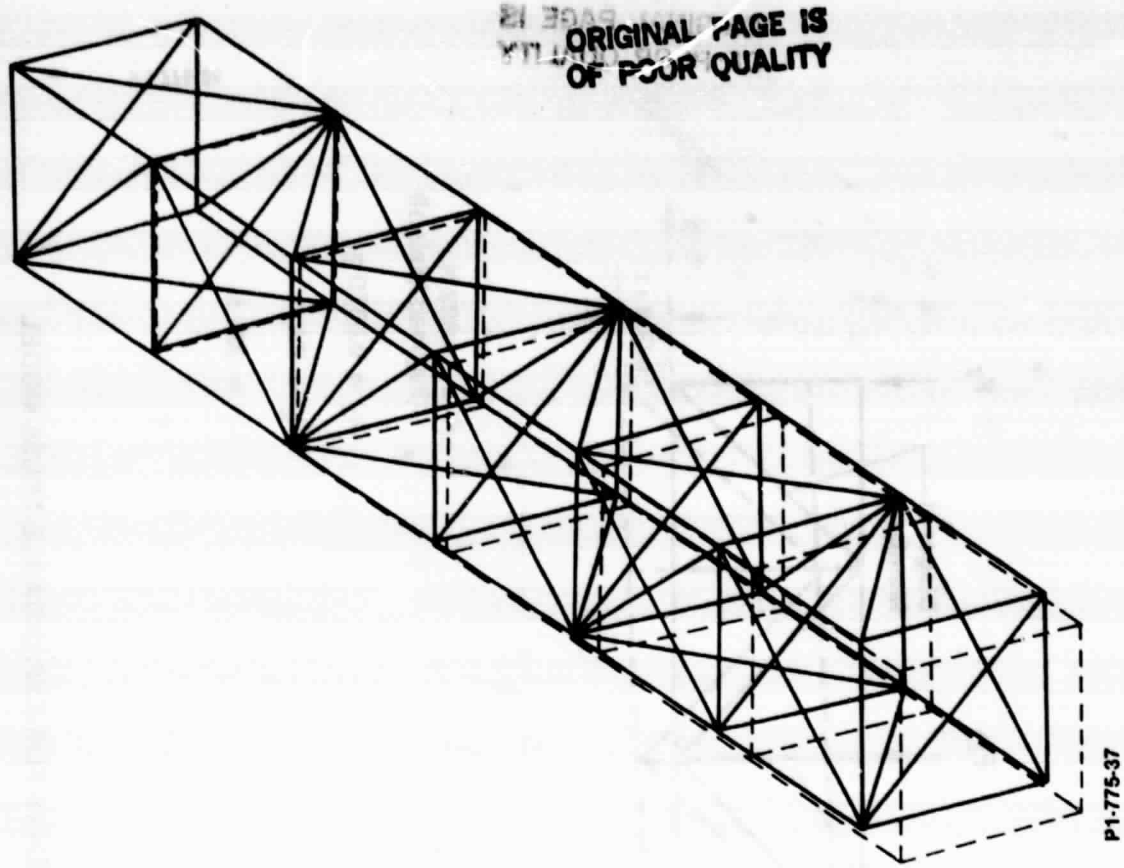

Figure 5-3 BENDING MODE 1 ("FIRST" –DIAGONAL)

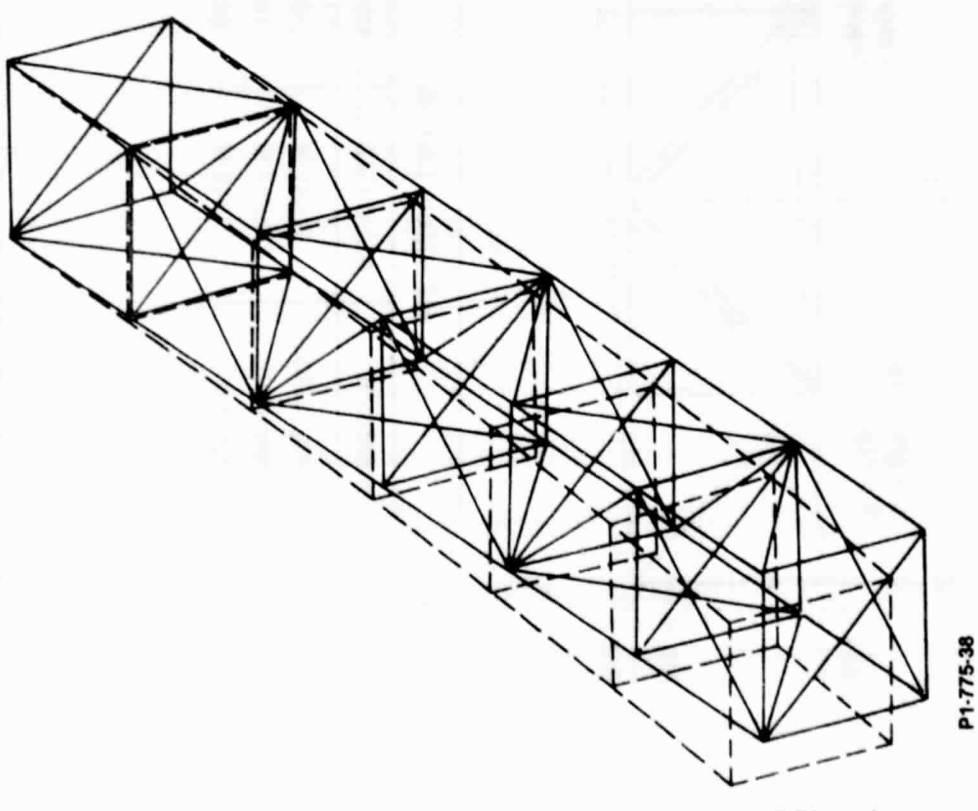

Figure 5-4 BENDING MODE 2 ("FIRST" – DIAGONAL)

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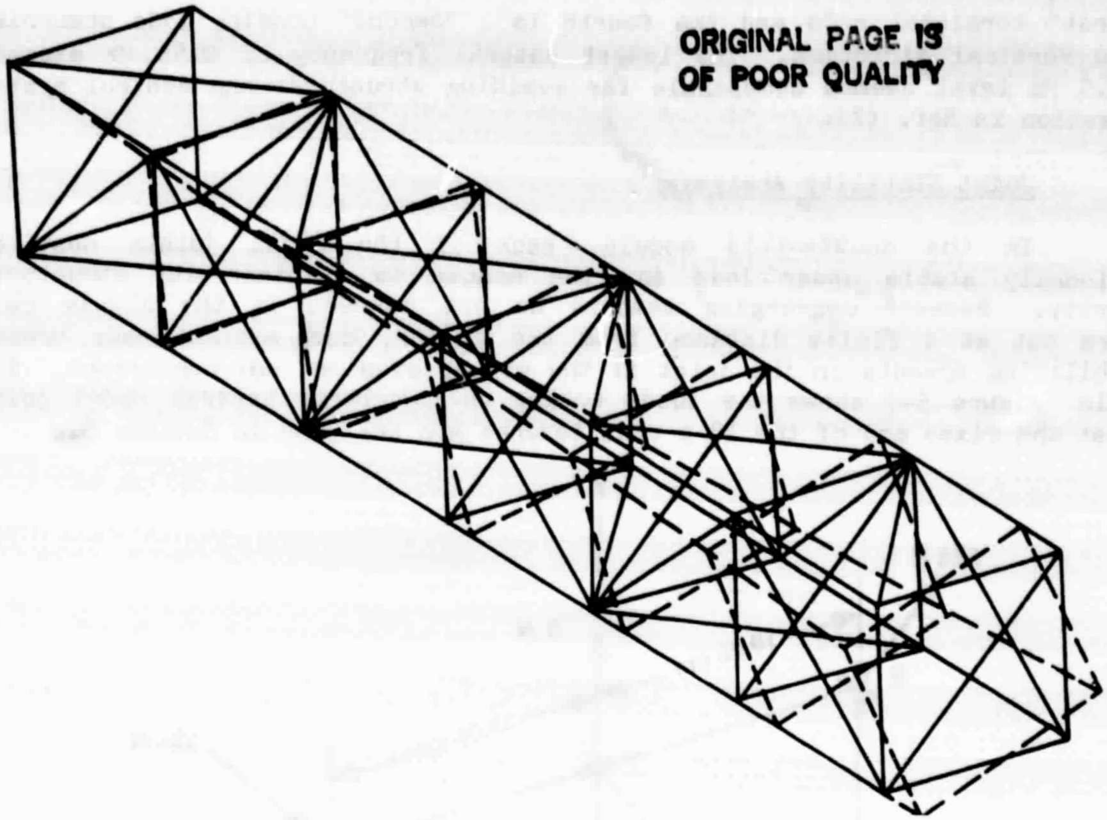

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Figure 5-5 BENDING MODE 3 ("FIRST"–TORSIONAL)

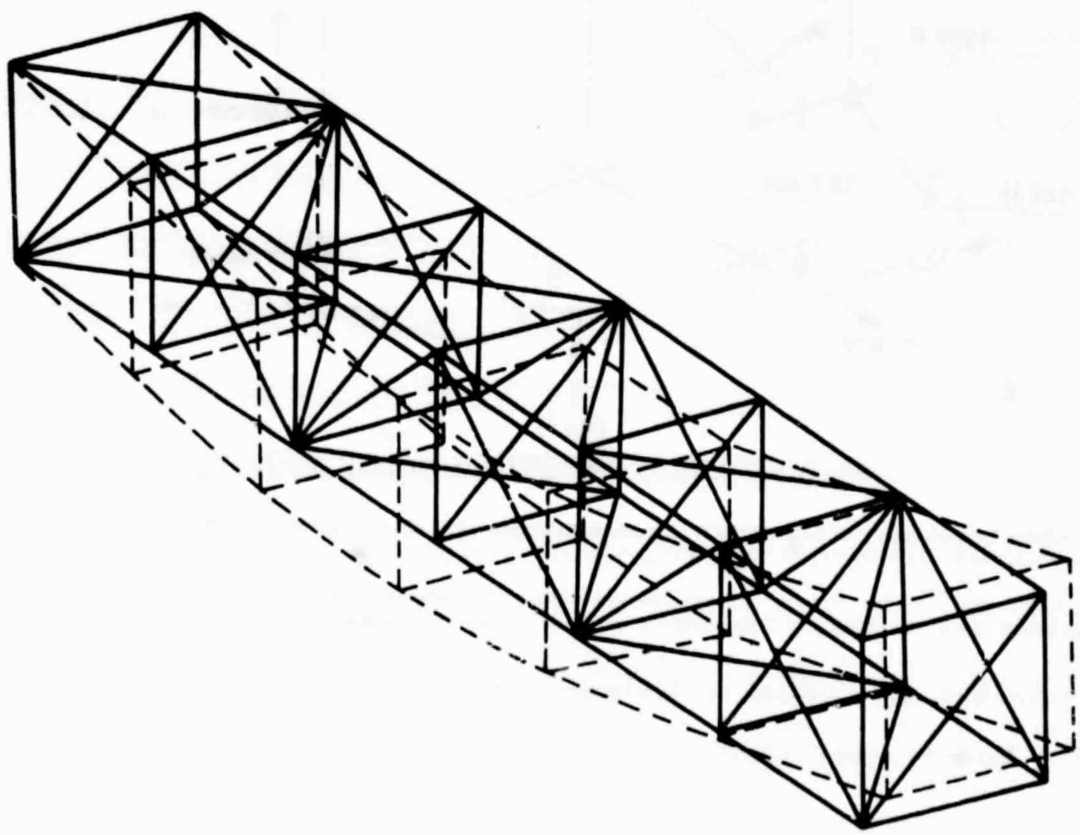

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Figure 5-6 BENDING MODE 4 ("SECOND" – VERTICAL)

a "first" torsional mode and the fourth is a "second" bending mode occurring in the vertical direction. The lowest natural frequency of 0.55 Hz exceeds the 0.5 Hz level deemed acceptable for avoiding structural and control system interaction in Ref. (7).

5.4 Joint Stability Analysis

In the double-fold module, each of the nodal joints must be rotationally stable under load for the module to maintain its structural integrity. Because converging members do not connect at the module cell corners but at a finite distance from the corner, compression loads create destabilizing moments on the joint if the member axes are not concurrent. For example, Figure 5-7 shows the loads acting on the large central nodal joint nearest the fixed end of the 18 m cantilevered arm analyzed in Section 5.2

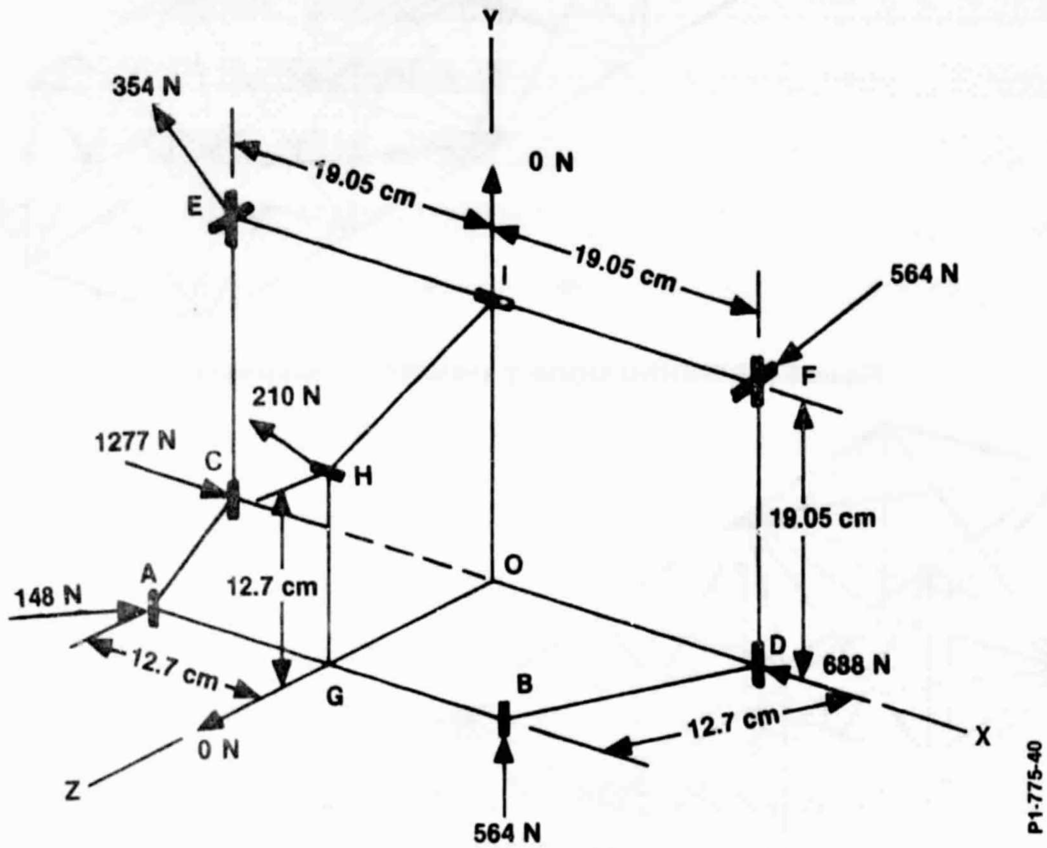


Figure 5-7 LOADS ON CENTRAL NODAL JOINT

under the critical transverse acceleration of 0.0079 g. (Recall that this critical acceleration was based on buckling the diagonal under highest load.) The joint is fixed to a lateral member at point G, but all other member connections are hinged. The solid black lines at the nodes indicate the hinge pin axes. The joints at E and F have two rotational degrees-of-freedom. If the joint has an initial rotational misalignment about the y-axis, the compressive loads, primarily those in the longerons attached at C and D, create a moment about point O which tends to increase the rotation. The primary restraint to rotation about the y-axis is the lateral member attached

at G. Similarly, rotations about the x-axis are restrained by the lateral at G with additional restraint by the diagonals hinged at A and B. Several members restrain z-axis rotations; including, in particular, the longerons at C and D as well as the lateral member at I and the diagonals at A, B and H.

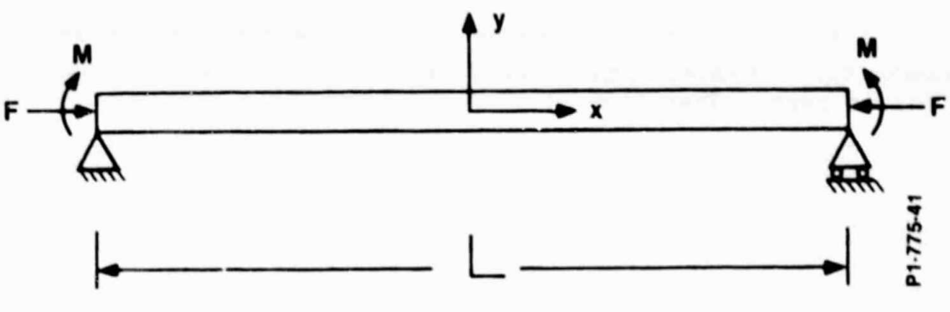
An inspection of all of the joints in a double-cell-double-fold module reveals that each is restrained in each of the three rotational degrees-of-freedom by at least a rigidly attached lateral member or by a longeron. Furthermore, under the critical transverse acceleration loading (0.0079g), the member loads are such that the greatest destabilizing moment for a given angular misalignment for all joints is for y-axis rotation of the large central joint of Figure 5-7. Hence, if it can be shown that a single longeron or lateral member is sufficient to stabilize a joint under the worst case moment, then all joints are stable.

For y-axis rotation of the center joint in Figure 5-7, the destabilizing moment about point O is:

$$M_O = [512 \text{ N-m/radian}]\ \theta_y \qquad (1)$$

where θ_y is the angle of rotation about the y-axis. Equation (1) was obtained assuming that joint rotation is small and does not change the direction of the joint forces but merely shifts their lines of action to create a moment arm about point O.

To show stability, consider the beam-column of Figure 5-8 with compressive load F and moment M acting on each end. The beam-column



$$M = A[\theta_o + \frac{dy}{dx}(x = L/2)$$

Figure 5-8 Beam Column for Joint Stability Analysis

represents a stabilizing longeron or lateral and the moment is assumed to act on both ends because that represents the worst possible situation in which joints on opposing ends act together to buckle the member. The differential equation for deflection of the beam-column is:

$$EI\ \frac{d^4y}{dx^4} + F\ \frac{d^2y}{dx^2} = 0 \qquad (2)$$

For simplicity, the origin X=0 is taken at the beam midpoint so that symmetry can be used to derive the boundary conditions:

$$y(\frac{L}{2}) = 0 \qquad EI \frac{d^3y}{dx^3}(0) = 0$$

$$\frac{dy}{dx}(0) = 0 \qquad EI \frac{d^2y}{dx^2}(\frac{L}{2}) = A[\theta_o + \frac{dy}{dx}(x = L/2)] \tag{3}$$

The third condition reflects the fact that the shear force is zero at mid span by symmetry, and the last condition is the moment equation at the joint. θ_o is some initial misalignment angle and A is the moment per unit angle of rotation. The total end rotation is θ plus the additional rotation $\frac{dy}{dx}(X=\frac{L}{2})$ due to elastic deformation.

The solution to Equations (2) and (3) is easily found:

$$y(x) = \frac{A\theta_o[\cos Kx - \cos(\frac{kL}{2})]}{Ak \sin(\frac{kL}{2}) - k^2 EI \cos(\frac{kL}{2})} \tag{4}$$

$$\text{where } k = \frac{F}{EI}$$

Joint instability exists for parameter values yielding unbounded deflections for non-zero θ_o. Hence, instability is obtained if the denominator in Equation (4) is zero. That is:

$$Ak \sin(\frac{FL}{2}) - k^2 EI \cos(\frac{kL}{2}) = 0 \tag{5}$$

or

$$A_{crit} = \frac{kEI \cos(\frac{kL}{2})}{\sin(\frac{kL}{2})}$$

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Thus, the critical joint moment per angle of rotation is a function of beam length, stiffness, and axial compressive load. For values of A less than A_{crit}, the joint will be stable.

Hence, if A_{crit} is greater than the value 512 N-m/radian from Equation (1) for all longerons and laterals, then all the joints are stable.

In calculating A_{crit}, the worst case condition holds when the compressive load F is a maximum. From Figure 5-2, for longerons, F_{max} = 1454 N and for lateral members, F_{max} = 187 N. Thus, for longerons,

F = 1454N
L = 3m
EI= 5912 N-m^2
(6.35 cm OD, .089 cm wall thickness aluminum)

which yields:

A_{crit} = 3,186 N-m/radian.

For lateral members,

F = 187N
L = 3m
EI = 1,182 N-m^2
(3.175 cm OD, 0.159 cm wall thickness aluminum)

which yields:

A_{crit} = 692 N-m/radian.

Since the calculated values of A_{crit} for both longerons and laterals are greater than the maximum value of 512 N-m/radian for the maximum loading condition, the analysis indicates that all joints are stable.

Although this analysis shows that the deflections of stabilizing members will remain finite, no consideration has yet been given to the restraint force magnitudes. Structural failure could still occur if the bending stresses in the stabilizing members or the nodal joint are too large. The bending moment at the joint is obtained by differentiating Equation (4) twice:

$$M\left(\frac{L}{2}\right) = EI\frac{d^2y}{dx^2}(x = L/2) = \frac{-A\theta_o\ kEI\cos\left(\frac{kL}{2}\right)}{A\sin\left(\frac{kL}{2}\right) - kEI\cos\left(\frac{kL}{2}\right)} \qquad (6)$$

The moment is proportional to the initial joint mislignment angle θ_o. A reasonable maximum value of θ_o is 0.0067 radians, corresponding to a misalignment of 0.25 cm over the 38 cm span of the largest space joint. Using this value of θ_o and A = 512 N-m/radian, together with the values of F, L, and EI for lateral members used previously to calculate A_{crit}, we find that the maximum restraining moment for lateral members is M (L/2) = 13.2 N-m.

For longitudinal members, the moment is smaller. A moment of 13.2 N-m (116.6 in-lb) is well within the strength capabilities of the members, nodal joints, and hinges. For example, a 13.2 N-m bending moment acting on a representative 1.27-cm (0.5 in) square cross section induces a tensile stress

of approximately 3,900 N/cm^2 (5,600 psi), much less than the tensile strength of the aluminum alloys used in the neutral buoyancy test hardware.

5.5 Static Load Test

This section decribes and discusses load testing of the asembled neutral buoyancy test structure. The purpose of the test was to determine the force-deflection characteristics under cyclical loading. Of particular interest were the determination of the structural hysteresis and detection of any joint free play. Hysteresis is important as it contributes to vibration damping for the flight structure. Joint free play is highly undesirable because it degrades the geometric integrity of the structure, contributing to pointing inaccuracy and other performance irregularities.

The test configuration is shown in the photograph of Figure 5-9. The test structure consisted of the fully assembled neutral buoyancy truss made up of two double-fold modules joined by the module-to-module interconnect for a total length of 15 m. One end was attached to a wall (Figure 5-10) by means of module-to-module couplers, and the structure was supported on the floor by rollers (Figure 5-11). These rollers provided essentially frictionless support, allowing unrestrained transverse deflection of the arm. The cantilevered arm was equally loaded on the top and bottom corners at the free end by a system of weights, ropes, and pulleys. Provision was made for loading in opposite directions, and load increments were applied by adding or removing weights. Bending deflections of the truss were measured at five module nodes (3m intervals) by dial indicators mounted on the floor (Figure 5-12).

Prior to testing the structure under load, no free play could be detected. Displacing the arm slightly from the equilibrium position by hand and then releasing it produced a damped oscillation which decayed to essentially the original rest position (within about 0.0254 mm as indicated by the dial gages.) Figure 5-13 is a plot showing the test results.

5.6 Hysteresis

When reviewing the results of the static test, evidence of a surprising amount of hysteresis was observed. An investigation was warranted because of the potentially detrimental results of having variable structural distortions between a control module and a pointing experiment.

Fundamentally, hysteresis is as necessary to structural damping as it is deleterious to the shape of a close tolerance variably loaded structure. The problem is to determine the magnitudes and frequencies for a given design such that the end product performs its intended functions satisfactorily.

Although a complete analysis was not within the scope of this contract, the following items show the need for further study to establish design criteria.

Total measured deflection results were influenced by these basic phenomena:

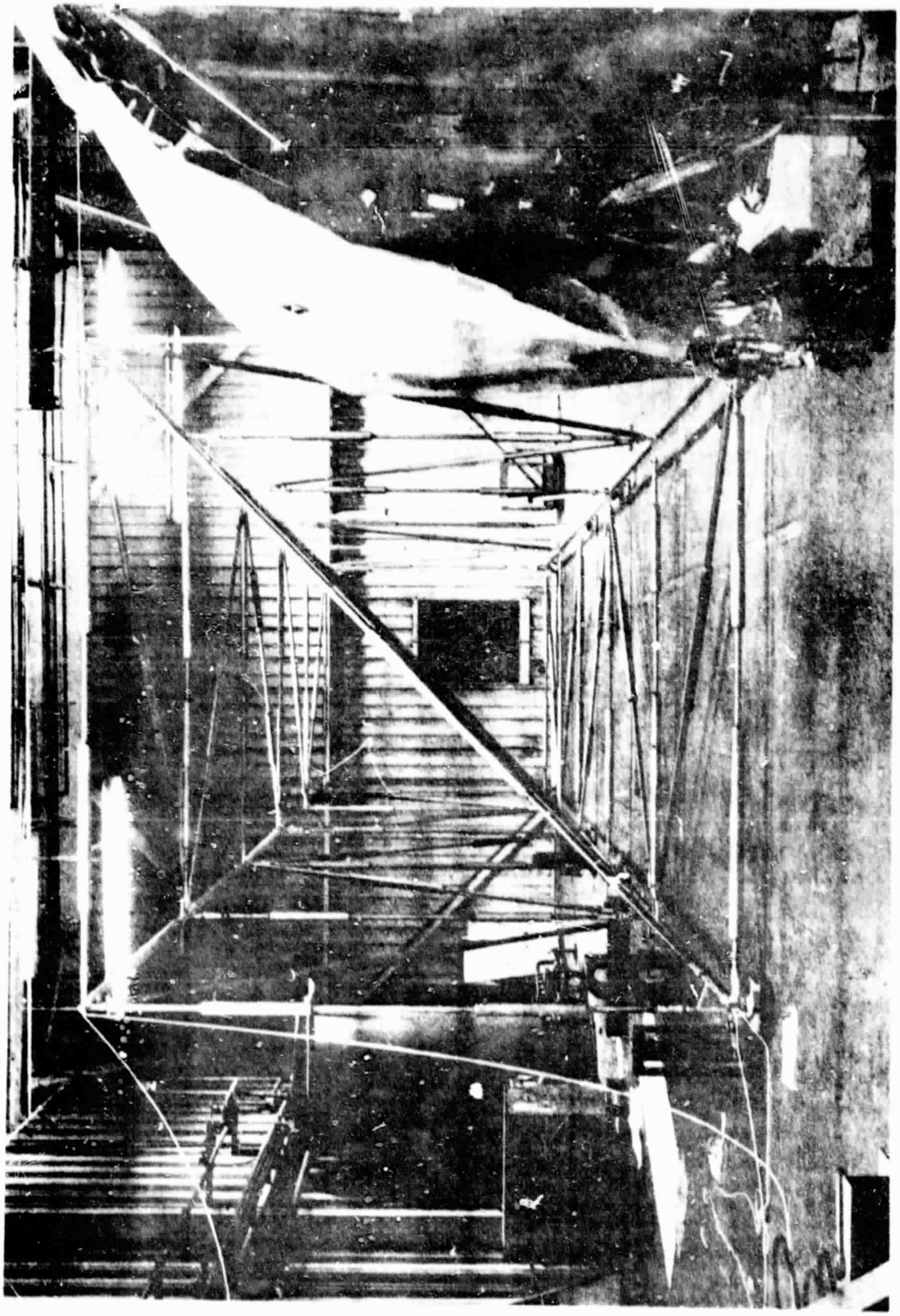

Figure 5-9 Deflection Test Setup

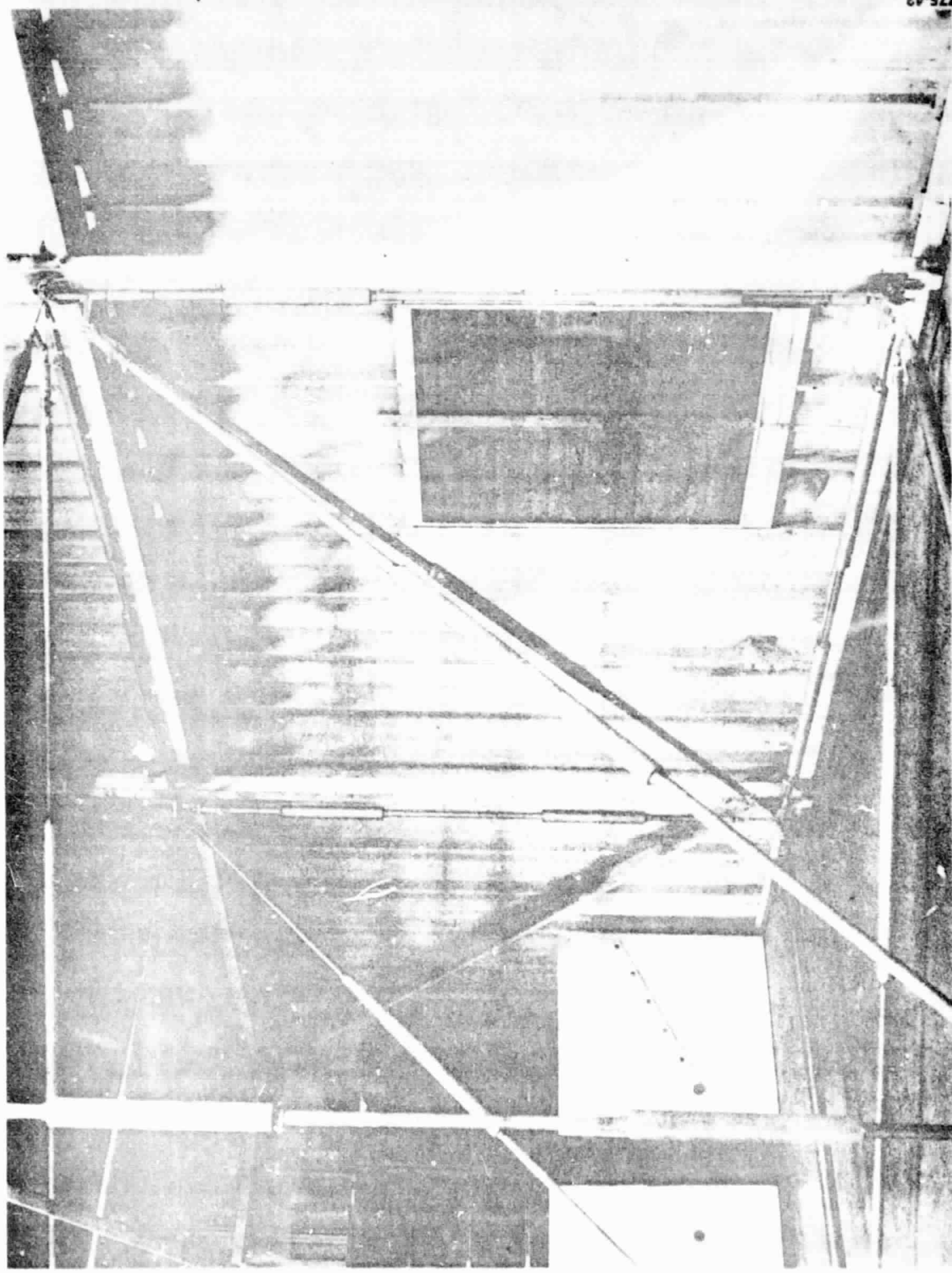

Figure 5-10 Test Restraint

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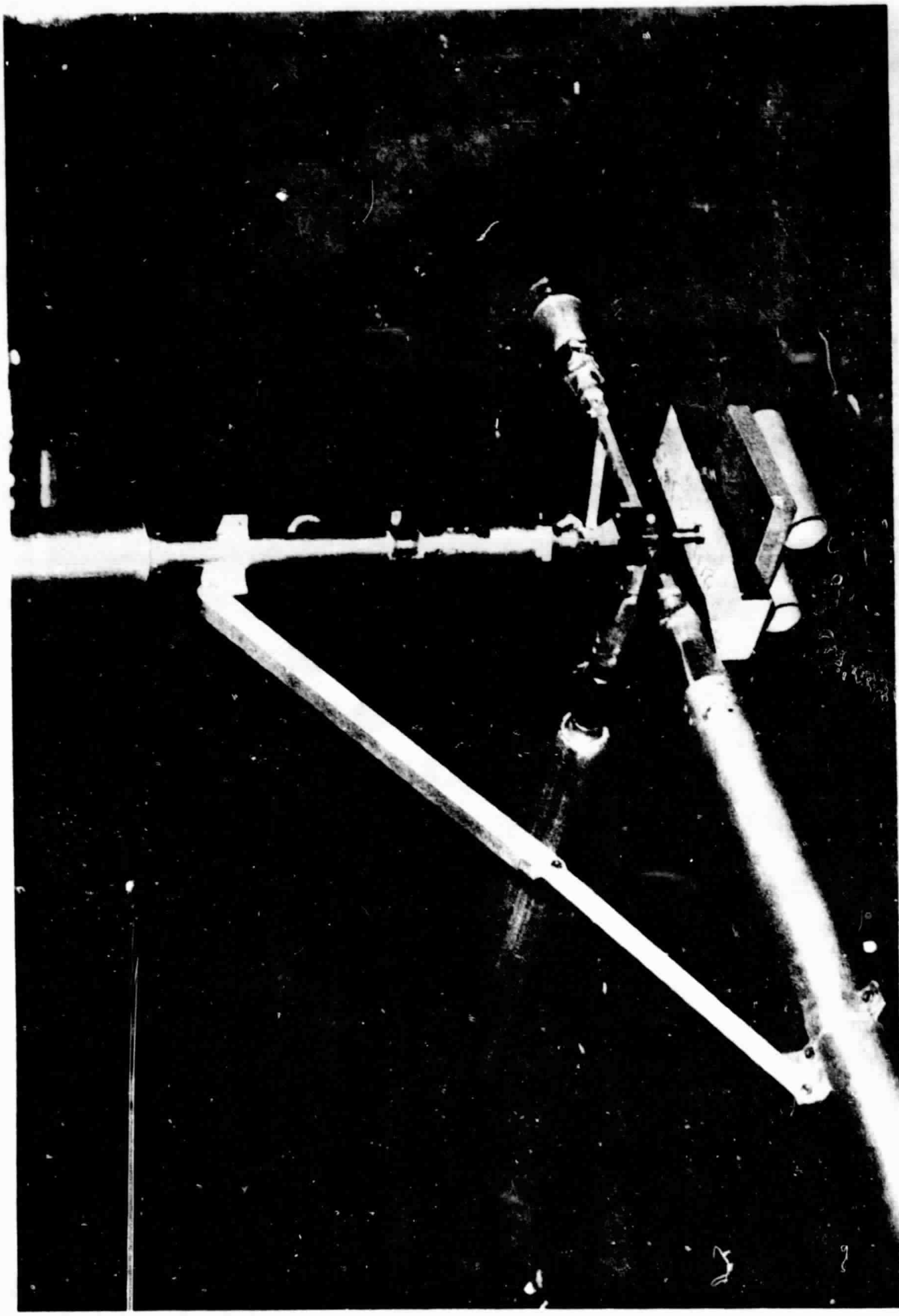

Figure 5-11 Lateral Roller

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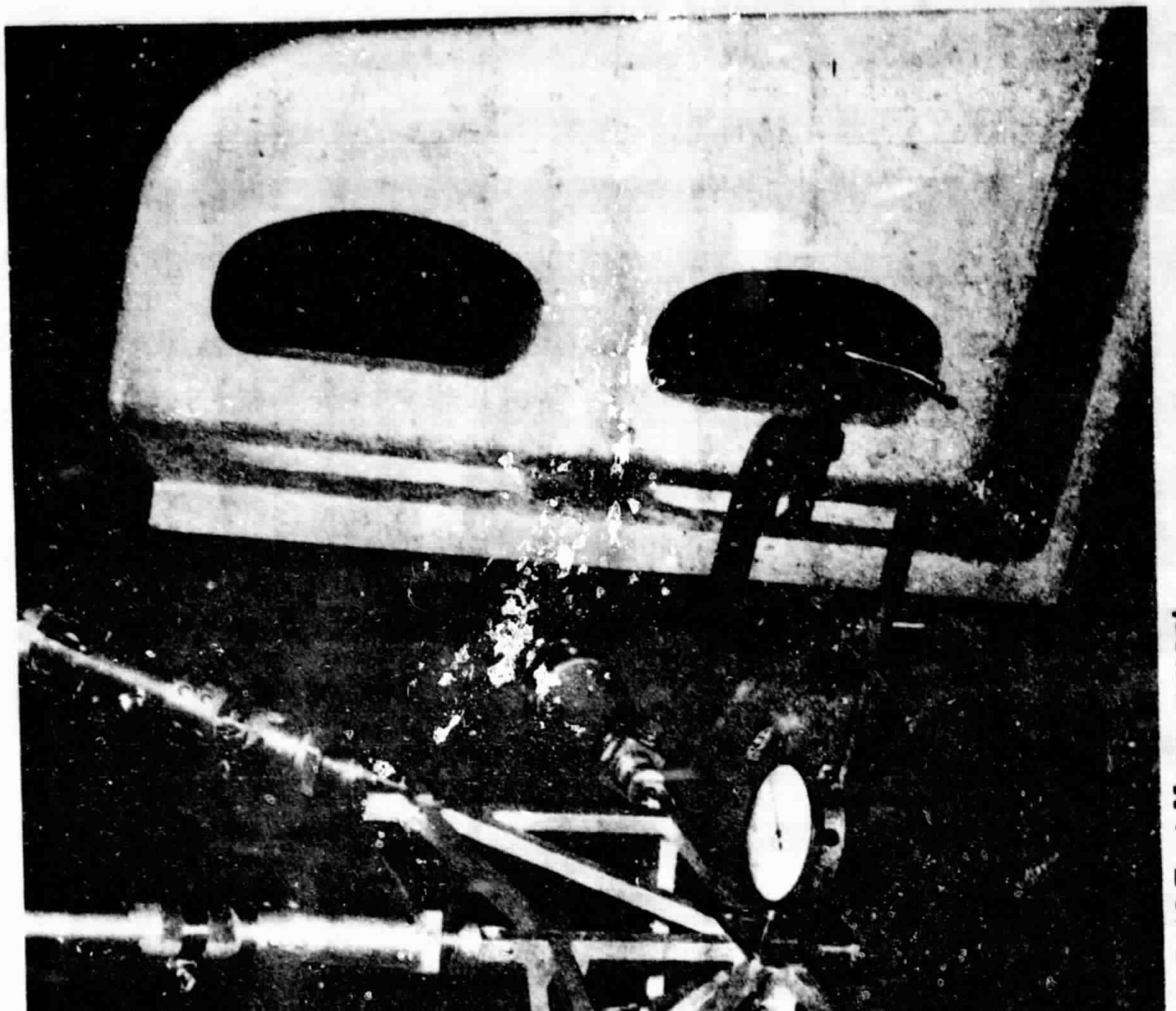

Figure 5-12 Test Measurement

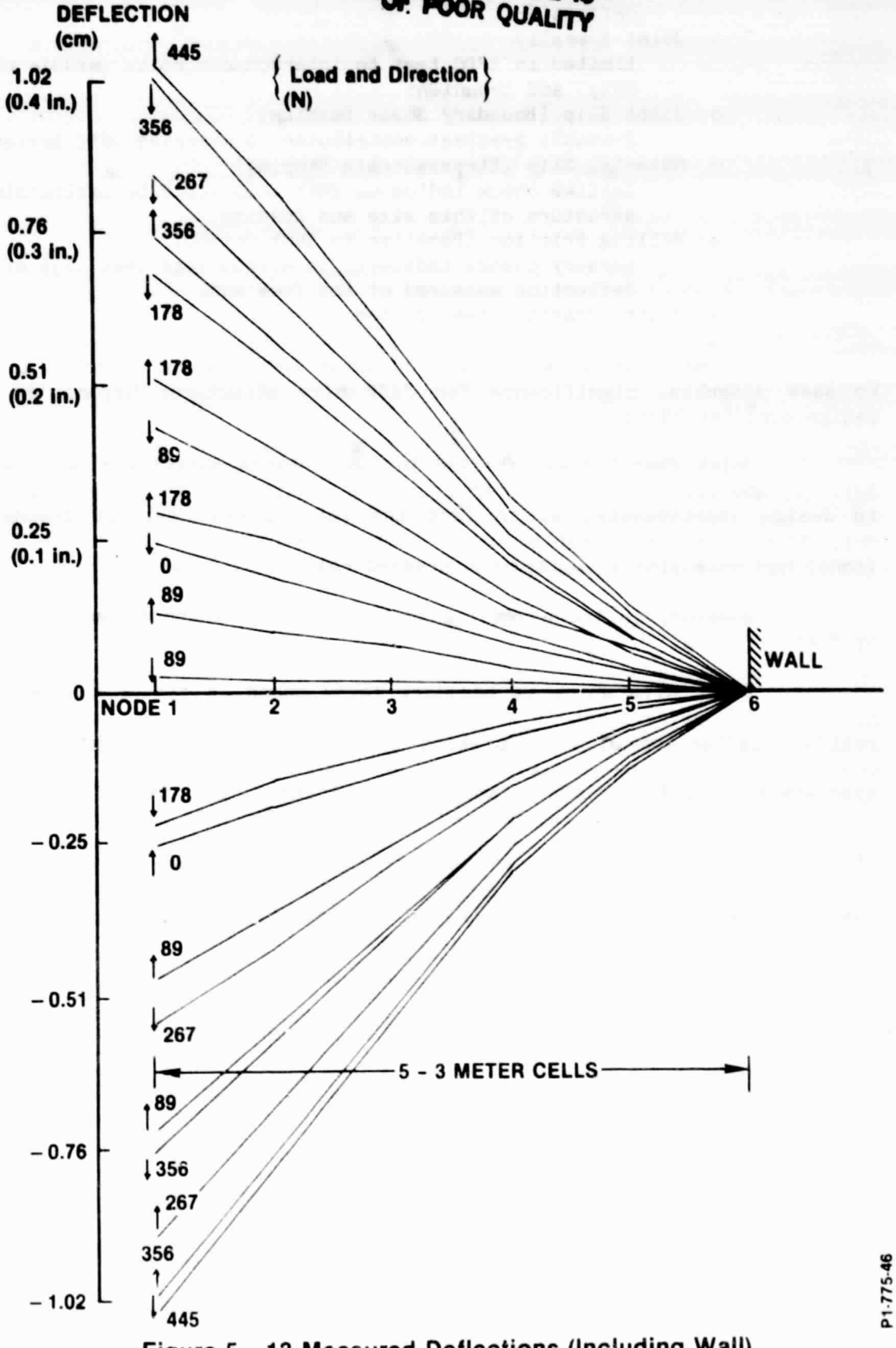

Figure 5—13 Measured Deflections (Including Wall)

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- o Strain (elastic strain under load)
  Represents the major portion (≈75%) of the observed deflection.
- o Joint Freeplay
  Limited in DFDC test to interconnect bolts (middle bay only) and trunnions.
- o Joint Slip (Boundary Shear Damping)
  Probably greatest contributor to observed DFDC Hysteresis.
- o Material Slip (Stress-Strain Damping)
  Initial check indicates that this would be negligible for structure of this size and loading.
- o Rolling Friction (Peculiar to Test Set-Up)
  Cursory checks indicated an effect less than .25% of total deflection measured at the free end.
- o Joint rotation (see Section 5.4)

Of the above items, only two, joint freeplay and joint slip, appear to have potential significance for SASP size structures beyond the normal design considerations.

Joint freeplay was studied in considerable detail and reported on by Ref. (1) and (2). It is considered to be a condition that is readily amenable to design improvements, as in fact the subject test article demonstrated. Only 22 of the 135 moveable joints in the test article (including telescope locks) had potential freeplay (not pressed roll pins, etc.).

However, in the assembled test set up, no looseness was discernable by feel or sound.

Joint slip which is boundary layer shear on the molecular level is not a usual consideration in structural design. Figure 5-14, however, shows a residual deflection of 0.1 cm which could translate into a pointing error, conceivably exceeding 1 arc min in an eighteen meter SASP arm. This is approximately 10% of the stability requirement and 5% of the accuracy requirement for pointing recommended by Ref. (8) for this type structure.

Of course the actual angle is dependent on which joints slipped, i.e.: permitting shear or bending type deformations. Further, this forces the conclusion that residual torsional deformations can also occur, affecting pointing accuracy of side mounted experiments.

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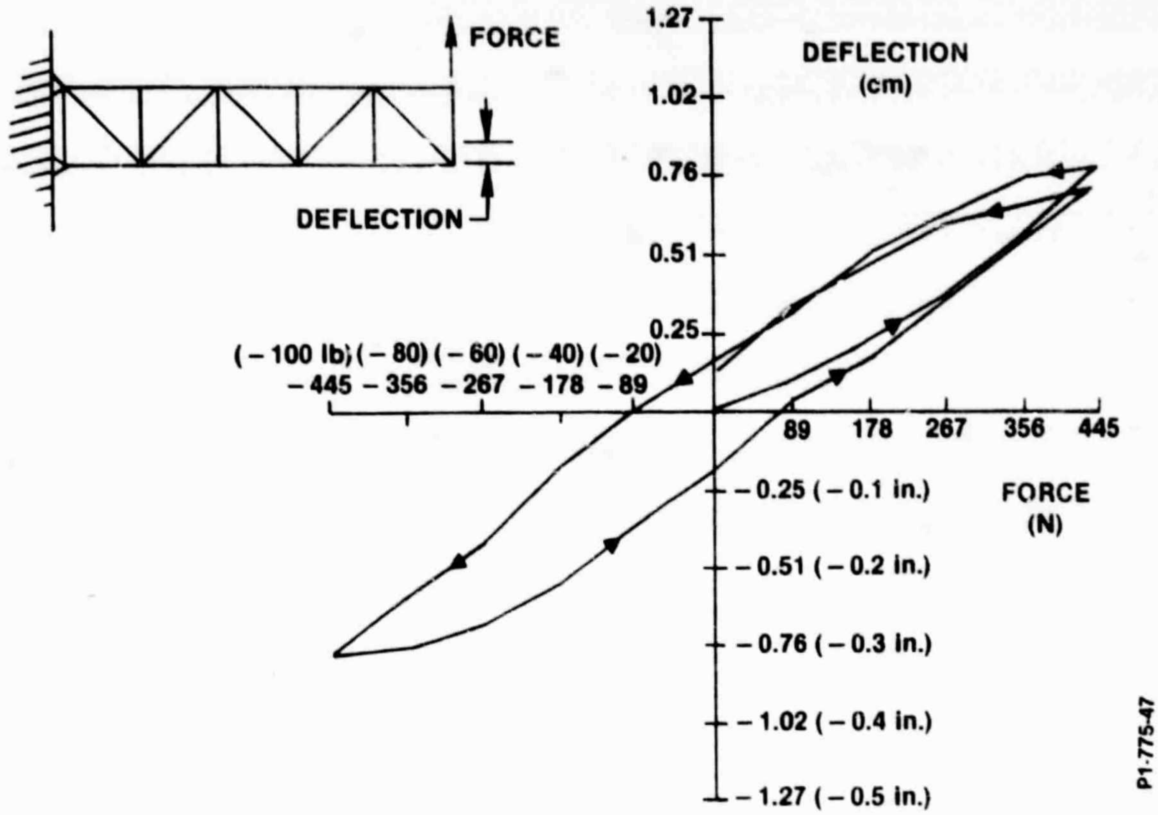


Figure 5—14 Static Influence Coefficient Data (With Wall Deflections Subtracted)

6.0 NEUTRAL BUOYANCY SIMULATOR (NBS) TESTING

The NBS tests conducted in September 1980 represented the culmination of the major effort of the Phase II portion of Vought's studies of Space Structure. The design, analysis and fabrication efforts were complete and the hardware was installed in the MSFC NBS Facility during the week of 5 September 1980.

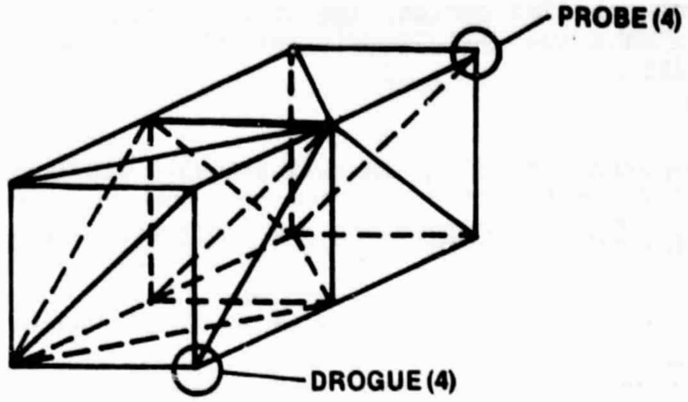
The test was planned for the underwater environment where a weightless environment could be realistically simulated. The hardware and EVA Subjects were made neutrally buoyant and balanced to avoid rotational tendencies. Thus, the hardware and Subjects react as if weightless with little difference expected in similar on-orbit operations (conclusion by Reference (4)). Operational timelines obtained from the tests are also expected to be realistic data from which to project on-orbit timelines. Early in the program Ref. (10) was prepared for guidance during the test article design. Later, the Test Plan, Ref (9) was prepared to finalize the test requirements, establishing the configuration of the test article and supporting hardware.

The Test Plan presented step-by-step operations for the nineteen proposed deployment/retraction tests and specified such things as RMS involvement, number of EVA Subjects involved, stowage configurations, location of deployment operations and sequence of lock/unlock operations.

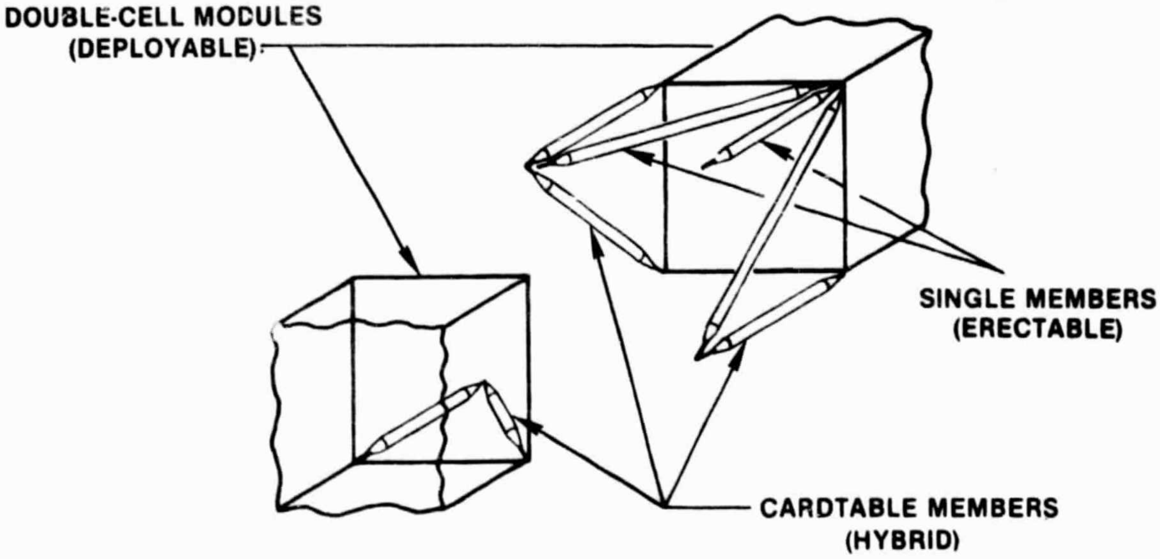
6.1 Test Objectives

The basic structure was divided into the elements shown in Figure 6-1. The rationale for this setup was derived such that the operational characteristics for the following elements could be demonstrated:

- o Basic structural module deployment and retraction.
  - The two bay DFDC represents a minimum length configuration for complete operational characteristics.
- o Module-to-module connection
  - Direct connection.
  - Indirect connection with 3 meter interconnect to eliminate bulkhead redundancy at interface.
- o Erectable and Hybrid Structure - Interconnect
  - The folding "cardtable" legs represent hybrid erectable/deployable structure which could be used in particular packaging schemes other than the single and double fold.
  - The single member, purely erectable, concept was included by substituting two loose members (after three point connection stability was established) for one of the "cardtable" legs.
- o EVA vs RMS Operation
  - The Test Plan was designed to determine the appropriate ratio of EVA and RMS involvement in the operating sequence.
  - The Plan also was set up to reveal design change potential for reducing operational constraints in both physical limitations and timelines.



(A) DOUBLE-CELL MODULE WITH COUPLERS



(B) MODULE-TO-MODULE INTERCONNECT

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Figure 6-1 Test Hardware Components

6.2 Test Preparation

In addition to preparing the Test Plan the following items were accomplished:

- o The hardware was checked and balanced in detail for neutral buoyancy.
- o A pre-test visit was made to the MSFC NBS facility to brief NASA and associated contract personnel on the double fold-double cell (DFDC) operations.
- o The Vought Project Engineer prepared and qualified for assisting in the NBS facility.
- o Vought assistance was provided for uncrating and installing the DFDC in the NBS, and for configuration changes during the test.

6.3 Test Operations

NASA personnel directed and controlled all test operations and directed or concurred with all plan changes.

Of the nineteen planned tests, fifteen were actually executed one or more times. Two were deleted due to tank space limitations on the fully deployed structure and two due to limited sensitivity of the RMS simulator.

The EVA subjects, RMS operator and support divers were "run through" each basic test in SCUBA gear for familiarization. Certain operations were delegated to the support divers for the following reasons:

- o When it was determined that a more sensitive RMS could accomplish the task.
- o When it was determined that a design change would eliminate the task, or make it feasible for EVA or RMS operation.
- o When it involved a step skipped in test preparation.
- o When it involved a maintenance type operation.

The Test Plan was modified on site during the operation in a few instances. For example:

- o The sequence was modified to take full advantage of the currently installed support structure configuration, thereby reducing setup changes between tests.
- o The release lever on the module coupler was found to have an exposed tip on the safety wire, presenting a small hazard to the divers. The levers were removed and used as an EVA tool pending redesign.
- o The stabilizers (stay braces) were not installed on the interconnect cardtable legs due to the tedious adjustment procedure required to assure proper positioning.

Typical test activity involved unstowing (i.e. releasing latches, holddowns, etc.), deploying, transporting, and attaching the structural elements. Figure 6-2 illustrates two single-folded modules stowed, Figure 6-3 shows two independently stowed double modules, Figure 6-4 shows two connected double fold modules for a 12 m arm nd Figure 6-5 shows the single fold stowage configuration adapting to the module-to-module interconnect.

In some tests, the objective was to restow the structural components

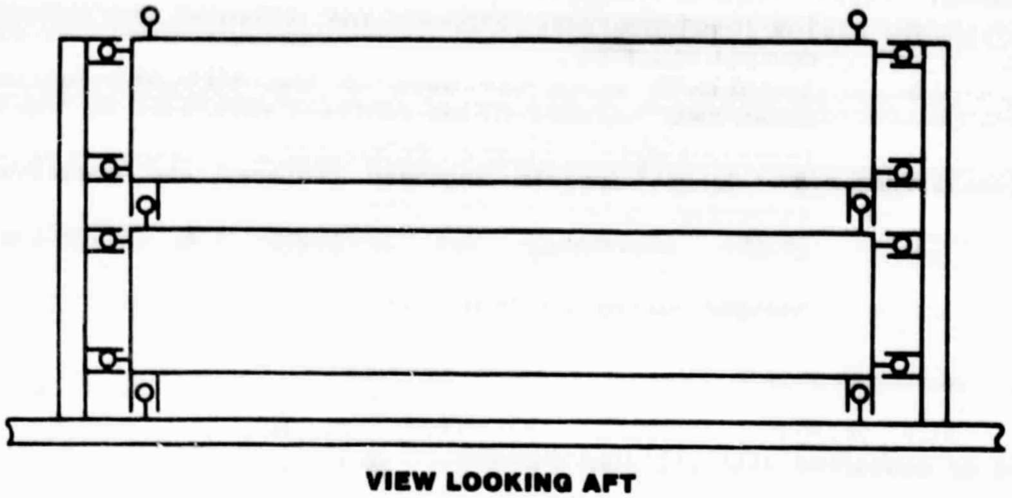

Figure 6-2 Single-Fold Stowage for Test 1 through Test 9

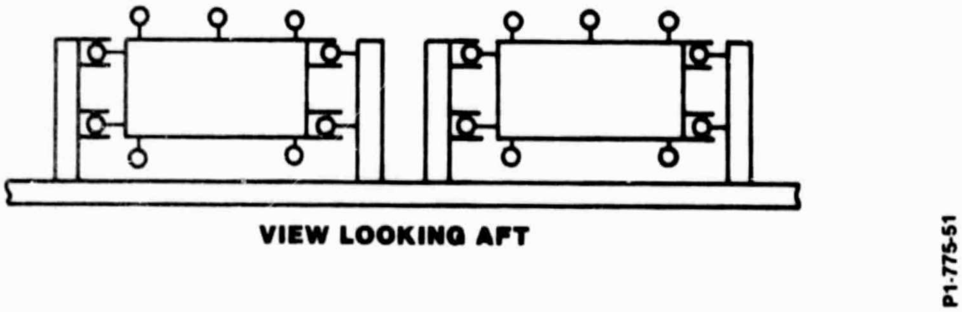

Figure 6-3 Double-Fold Stowage for Test 10 through Test 14

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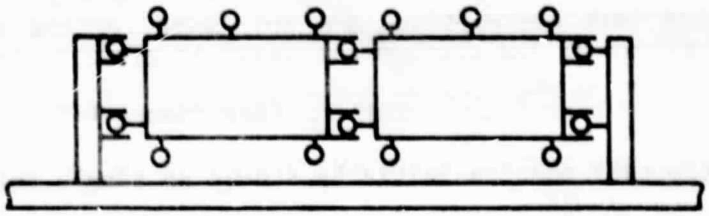

Figure 6-4 Connected Double-Fold Stowage for Test 15 and Test 16

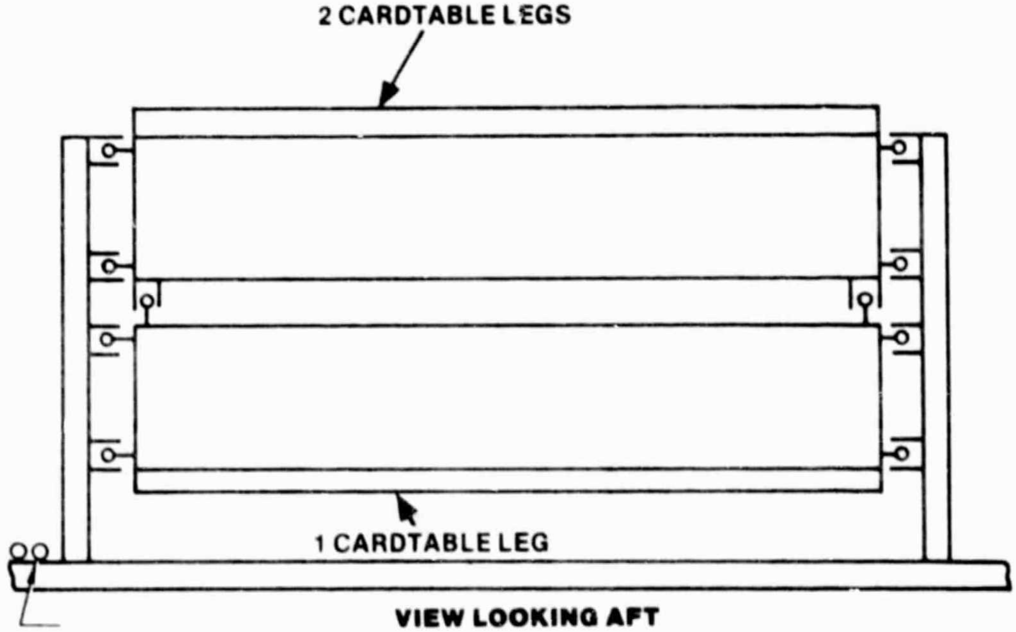

Figure 6-5 Single-Fold Module with Cardtable Leg Interconnect Stowage for Test 17 through Test 19

starting from an already assembled structure. For restowing, the procedures are essentially the reverse of the assembly procedures.

The procedures outlined here consist of several basic tasks to be performed to accomplish a specific objective. Because there is much repetition, detailed task descriptions are not given for the sake of brevity. A step-by-step breakdown of the fundamental tasks is given in Ref. (9).

<u>TEST 1.</u> (See Figure 6-6)

- 2 double-cell modules initially stowed in single-fold configuration
- 2 EVA crew members

<u>PROCEDURE</u>:

(1) Unstow first module.
(2) Transport to aft mounting base.
(3) Attach to base at four corners.
(4) Unfold first module.
(5) Unstow second module.
(6) Transport to end of previously installed module.
(7) Attach second module to first module at four corners.
(8) Unfold second module.

<u>TEST 2.</u>

- 2 double-cell modules initially stowed in single-fold configuration
- 2 EVA crew members

<u>PROCEDURE</u>:

(1) Unfold first module in place.
(2) Release first module from support.
(3) Transport to aft mounting base.
(4) Attach to base at four corners.
(5) Unfold second module in place.
(6) Release second module.
(7) Transport to end of first module.
(8) Attach to first module at four corners.

<u>TEST 3.</u>

- 2 single fold modules initially connected and stowed
- 2 EVA crew members

<u>PROCEDURE</u>:

(1) Unstow modules.
(2) Transport folded modules to aft mounting base.
(3) Connect end of one module to base at four corners.
(4) Unfold module to form 12 m arm.

<u>TEST 4.</u>

- 2 double-cell modules initially erected on base
- 2 EVA crew members

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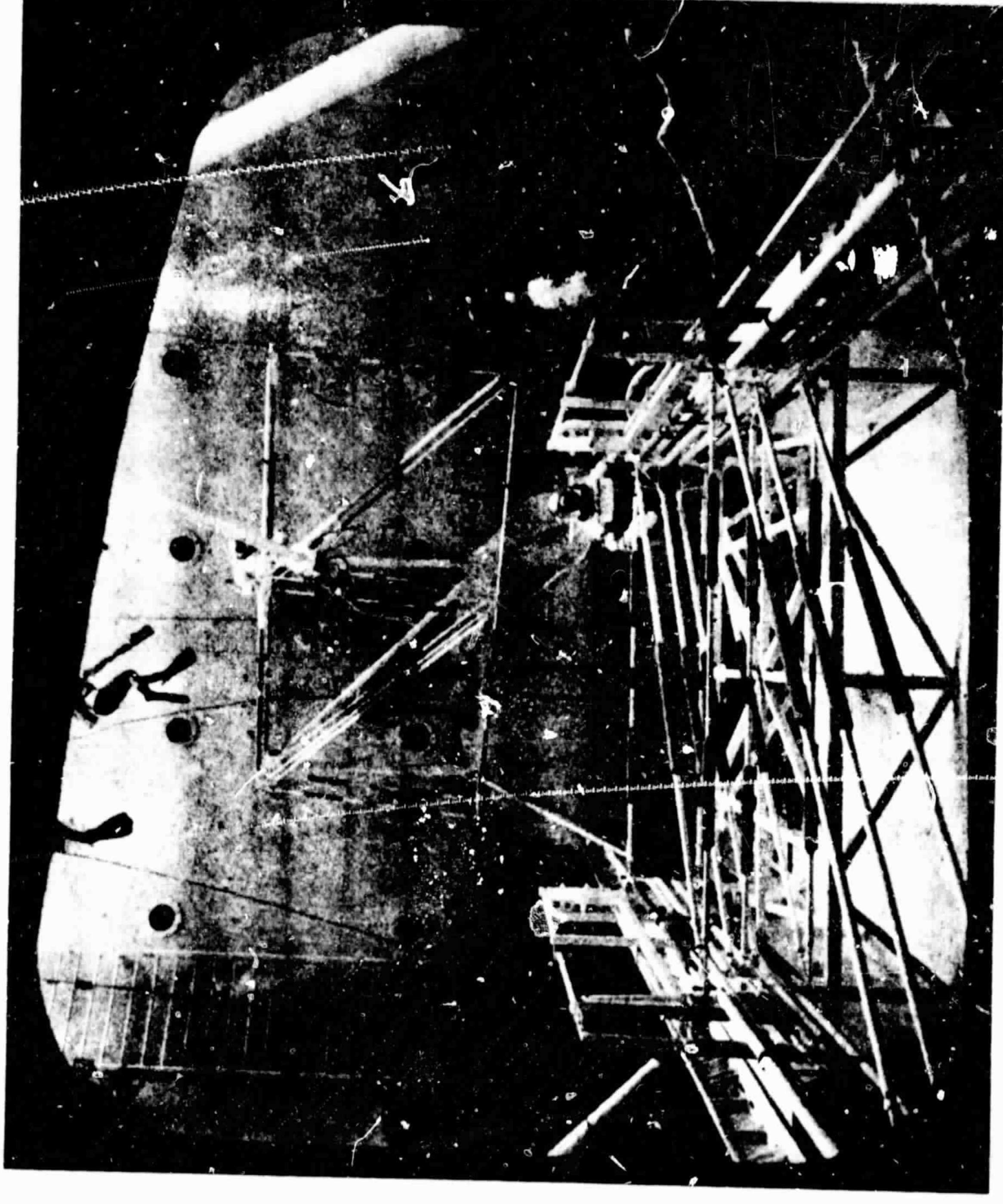

Figure 6-6 Test Number One

PROCEDURE:

(1) Fold free end module into single-fold configuration.
(2) Disconnect from other module.
(3) Transport folded module to payload bay pallet.
(4) Stow in single-fold configuration.
(5) Fold second module into single-fold configuration.
(6) Disconnect second module from base.
(7) Transport module to payload bay pallet.
(8) Stow in single-fold configuration.

TEST 5.

Repeat Test 1 using 1 EVA crew members.

TEST 6.

Repeat Test 4 using 1 EVA crew member.

TEST 7.

Repeat Test 2 using 1 EVA crew member.

TEST 8.

Repeat Test 3 using 1 EVA crew member.

TEST 9.

- 1 double-cell module initially stowed in single-fold configuration
- No EVA crew members, RMS only.

PROCEDURE:

(1) Unstow module.
(2) Transpoirt to aft mounting base.
(3) Attach to base at four corners.
(4) Unfold module.

TEST 10.

- 2 double-cell modules initially stowed in double-fold configuration
- 2 EVA crew members.

PROCEDURE:

(1) Unstow first module (partially).
(2) Perform first unfold while attached to payload bay pallet.
(3) Release first module from support.
(4) Transport to aft base support.
(5) Connect first module to base at four corners.
(6) Perform second unfold.
(7) Unstow second module.
(8) Perform first unfold while attached to pallet.
(9) Release and transport second module to end of first module.
(10) Connect second module to first module at four corners.
(11) Perform second unfold.

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TEST 11.

- 2 double-cell modules initially erected on base
- 2 EVA crew members

PROCEDURE:

(1) Fold free end module into single-fold configuration.
(2) Disconnect from other module.
(3) Transport folded module to payload bay pallet.
(4) Attach one side of module to support fixture.
(5) Perform second fold to place module in double folded configuration.
(6) Make remaining attachments to complete stowing.
(7) Fold second module into single-fold configuration.
(8) Disconnect from base.
(9) Transport second module to payload bay pallet.
(10) Attach to support fixture and perform second fold.
(11) Complete stowing of second module.

TEST 12.

Repeat Test 10 using 1 EVA crew member.

TEST 13

Repeat Test 11 using 1 EVA crew member.

TEST 14.

- 1 double-cell module initially stowed in double-fold configuration
- No EVA crew members, RMS only.

PROCEDURE:

(1) Unstow module sufficiently to allow first unfold.
(2) Perform first unfold.
(3) Release module from support and transport to mounting base.
(4) Attach to base at four corners.
(5) Perform second unfolding operation.

TEST 15.

- 2 double-cell modules initially connected and stowed in a double-fold configuration.
- 2 EVA crew members.

PROCEDURE:

(1) Unstow modules sufficiently to allow first unfold.
(2) Perf[illegible] first unfold while attached to pallet.
(3) Release modules from pallet and transport to mounting base.
(4) Connect end of one module to base at four corners.
(5) Perform second unfold to form 12 m arm.

TEST 16.

Repeat Test 15 using 1 EVA crew member.

TEST 17.

- 2 single-folded modules, two folded cardtable legs attached to one module, one cardtable leg attached to other module, 2 single members with end connections.
- 2 EVA crew members.

PROCEDURE:

(1) Unstow module with two cardtable legs.
(2) Transport to mounting bse.
(3) Attach module to base at four corners.
(4) Unfold module.
(5) Unfold two cardtable legs.
(6) Unstow module with one cardtable leg.
(7) Transport to end of first module.
(8) Unfold cardtable leg on second module.
(9) Join modules by attaching three cardtable legs.
(10) Unstow and attach loose longeron between modules.
(11) Unstow and attach loose diagonal between modules.
(12) Unfold second module.

TEST 18.

-2 double-cell modules joined by module-to-module interconnect and mounted on base.
-2 EVA crew members.

PROCEDURE:

(1) Fold end module into single-fold configuration.
(2) Remove and stow two single members.
(3) Detach three cardtable legs joining modules.
(4) Fold cardtable leg on first module.
(5) Transport first module to payload bay and stow in single fold configuration.
(6) Fold two cardtable legs on second module.
(7) Fold second module into single-fold configuration.
(8) Transport second module to payload bay and stow in single-fold configuration.

TEST 19.

Repeat Test 17 using 1 EVA crew member.

6.4 Test Results

In general the performance of the DFDC structure and associated hardware was rated by both NASA and their NBS support contractor to be excellent. The deficiencies that were shown to exist, some of which were cost/schedule related deletions from test article design, were all agreed to be fixable by design improvement.

6.4.1 Improvements Indicated For Orbital Operation

Although most of the design changes required or desirable are a direct result of cost limitations during the design and fabrication phases, all of the items that were noted are listed here for inclusion in the overall data base:

- o Roll pin retention -
  Although the suspected cause of loosened roll pins was overstressing of the lugs during one "G" handling without proper support equipment, it is considered mandatory that positive retainers be added.
- o Redesigned coupler release levers -
  The safety wire hazard must be removed and careful consideration given to positioning of the lever for proper access by EVA or RMS.
- o Thermal
  Other paint systems need to be investigated - Orbital requirements will be different from that of the NBS facility. (Also, the paint bubbling observed in the test article indicates a need for a better underwater paint system.)
- o Quality Control -
  Although this will be of necessity an overall aspect of flight design, the most obvious trouble spot in the test hardware occurred with the telescope locks. Paint was scraped off the "blades" and jammed the mechanism of several of the locks repeatedly.
- o Operation Indicators -
  For example if visual indication of lock/unlock conditions is elected, color coding will be required for the telescoping tube and coupler locks. Also, if retraction is planned, an indication of the fold and stowage orientation is desirable.
- o Packaging Stability -
  It was determined that a completely self sufficient packaging system built into the DFDC would be highly desirable. Solid stops and guides for folding and rigid retainers for each fold segment would:
  - support long slender members during launch
  - protect adjacent structural members from damage
  - permit sequential fold/unfold
  - reduce complexity of support structure
  - facilitate on orbit transport from support structure to base or other deployed module
- o Improved support/stowage structure -
  The test article was intentionally designed as a versatile, though minimum cost structure. A flight version will need to support the full length of the DFDC and interface with the other potential payloads and perhaps the Orbiter itself. However, the problem that was not well understood prior to the test was the difficulty caused by the DFDC couplers and probes hanging up in the open sided support structure during removal and stowage.

- Cardtable stabilizers -
  Although the interconnect is expected to be deleted (not being cost/weight effective when used in conjunction with the DFDC), the stabilizers were shown to be an almost mandatory part of the hybrid deployable/erectable "cardtable" concept.
  (NOTE: The cardtable concept is expected to be useful only for pancake stowage of a relatively short structure.)

6.4.2 Operational Timelines

The prediction of time required for operations performed on orbit is extremely important to everyone concerned in a space mission. Not only will accurate prediction permit selection of better designs and better operating procedures, it will aid in optimizing associated supporting equipment and supplies. The NBS Facility appears to be an extremely valuable tool for evaluating designs and procedures. The obvious extension of NBS usefulness would be that of training EVA Specialists and RMS Operators, such that on-orbit time is minimized.

The timelines presented here, Table 6-1 and 6-2, are taken from videotapes of the deployment/stowage operations performed at the NBS Facility at MSFC. Table 6-1 presents timeline totals for complete deployment/retract operations, and Table 6-2 gives timeline elements for selected operations. Appendix II includes the timelines as derived by the Essex Corporation.

Although at present restowing is not a planned on-orbit operation, these timelines are included. Since restow was, of course, required for repeated deployment tests, knowledge of the operations were considered to be valuable in the timeline study.

In general, as concluded in Ref. (4), the primary difference between NBS and on-orbit operations will be an improvement due to lack of water effects (primarily drag) and improved vision. Also, the Orbiter mounted RMS is more sophisticated and will be more useful than the simulator used in the NBS.

A note of caution should be added with regard to one effect of water drag; that of naturally slowing the movement of a large mass approaching its desired location. This is beneficial in some instances, and its loss must be accounted for in space operation planning to avoid excessive overrunning or collisions.

Figure 6-6 shows a typical test operation (No. 1) with the first module, single folded, being attached to the base frame ready for deployment. The second EVA Subject is in position to release the number two module from the support fixture.

SUMMARY-TEST RESULT MATRIX

TEST NO. \ CONDITION	SEPARATE DOUBLE CELL MODULE		INTER-CONNECT MODULE	EVA	RMS	DEPLOY		RETRACT		TIME LINE TOTALS (MIN:SEC)
	DOUBLE FOLD	SINGLE FOLD				BASE	ORBITER	BASE	ORBITER	
1		2		2	X	X				52:40
2		2		2	X		X			43:30
3 x		1		2	X	X				-----
4 o		2		2	X			X		-----
5		2 Δ		1	X	X				26:05 Δ
6		2 Δ		1	X			X		24:35 Δ
7		2		1	X		X			43:20
8 o		1		1	X	X				-----
9 x		1*		0	X	X				-----
10	2			2	X	X				42:35
11 o	2			2	X			X	X	-----
12	2			1	X	X	X			51:00
13 o	2			1	X			X	X	-----
14 x	1*			0	X	X	X			-----
15 o	1			2	X	X	X			-----
16 o	1			1	X	X	X			48:55 #1
17		2	X	2	X	X				39:40 #2 43:40 #3
18		2	X	2	X			X		17:30
19 x		2	X	1	X	X				-----

* SINGLE UNIT ONLY
x DELETED TEST
o NO TAPES AT VOUGHT
Δ 1 MODULE (UNIT) TESTED

TABLE 6-1

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TABLE 6—2 TIMELINES FOR DEPLOY OPERATIONS

OPERATION	EVA (1)	RMS	TIMELINE INCREMENTS (MIN: SEC / TEST NO.– MODULE NO.)							
A. UNSTOW SINGLE FOLD MODULE TO CLEAR SUPPORT	X	X	3 : 40 / 1-1	7:00 / 1-2	1:05 / 10-1	5:00 / 10-2	6:05 / 12-1	2:20 / 12-2	3:15 / 17-1	1:00 / 17-2
B. TRANSPORT MODULE TO AFT BASE		X	5:00 / 1-1	5:35 / 1-2	3:00 / 10-1	3:45 / 10-2	4:10 / 12-1	1:20 / 12-2	4:00 / 17-1	4:00 / 17-2
C. ATTACH MODULE AT FOUR CORNERS AND CHECK COUPLERS	X	X	1:20 / 1-1	2:50 / 1-2	3:55 / 10-1	1:55 / 10-2	8:45(2) / 12-1	4:00 / 12-2	1:05 / 17-1	
D. UNFOLD TWO CELL MODULE AND CHECK TELESCOPE LOCKS	X	X	16:05 / 1-1	11:10(3) / 1-2						
E. PARTIAL UNSTOW OF DOUBLE FOLD MODULE	X	X	0:30 / 10-1	4:50 / 10-2	0:30 / 12-1	5:15 / 12-2				
F. FIRST UNFOLD OF DOUBLE FOLD MODULE	X	X	5:45 / 10-1	5:45 / 10-2	1:15 / 12-1	5:20 / 12-2				
G. UNFOLD FOUR CELL MODULE AND CHECK TELESCOPE LOCKS	X	X	7:05 / 10-2	12:00 / 12-2	13:35 / 17-2					
H. UNFOLD TWO CARDTABLE LEGS	X		4:00 / 17-1							
I. ATTACH THREE CARDTABLE LEGS BETWEEN MODULES	X	X	6:30 / 17-2							
J. UNSTOW AND ATTACH LOOSE LONGERON STRUT	X		4:15 / 17-2							
K. UNSTOW AND ATTACH LOOSE DIAGONAL STRUT	X		1:50 / 17-2							

(1) Two EVA on all except test No. 12 which is with 1 EVA.
(2) Two EVA on opposite sides can couple modules much faster than one EVA.
(3) Last cell was deployed and locks checked by two EVA (no RMS) in 2:40 time.

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7.0 AUTOMATIC DEPLOYMENT STUDY

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The investigation of automatic deployment was designed to add to the LSST information data base some knowledge of the practicality, reliability, weight, volumetric effects and timeline advantages of automation.

This study derives information from the earliest Vought research and carries through several concepts for automating the double fold-double cell (DFDC) structure and the Vought IR&D developed biaxial scissors fold (BASF).

During the current and Phase I contracts, Vought studies covered literally dozens of design concepts and hardware designs for joints, members, couplers and deployment mechanisms from other sources. In addition, a few dozen more of Vought's own concepts were developed to varying degrees. Of these, the DFDC and BASF were selected to evaluate for automatic deployment.

Table 7-1 summarizes the concepts resulting from the DFDC and BASF Automation study. This table also references Figures 7-1 through 7-8 which show layouts for some of the basic concepts, and some detail layouts showing solutions to certain associated problems. These detail solutions were required to show feasibility before developing some of the basic concepts. A careful review of these concepts for practicability, relative cost, complexity, etc., resulted in the selection of Concept 6 for the DFDC and Concept 9 for the BASF as the most viable for further development in the next task.

7.1 Automatic Double Fold Structure (Concept 6)

Of the two concepts selected by Vought and presented to MSFC as the most promising, the Concept 6 for a DFDC was selected for further development in the next task (see Section 8).

A detailed description of deployment and refold characteristics is given, sequentially, below. The folding operation may be sequenced from first fold to second fold or permitted to simultaneously fold in both axes.

DEPLOYMENT (CONCEPT 6)

o Pulling a lanyard or energizing a release device, releases all cable ties wrapped around the bundle of structure.

o Each cable tie is retracted into its reel case so there will be no loose ends to snag deploying structure.

o A deployment tension spring is connected between 15.24 cm (6 inch) arms on each pair of longitudinal or lateral struts which pivot together as a parallelogram. See "A" dimension in Figure 7-10.

o The spring tension "T" acts on "A" and "B" to initiate deployment. The springs stay approximately parallel to the telescoping struts.

o As the structure deploys, dimension "B" increases to 70% of cell size "L", while "A" reduces to zero so that there is no deployment spring induced bending moment at the pivoting strut ends. Spring force reduces from about 31.14N (7 lbs) to 13.34N (3 lbs) during deployment.

MFS-25647

CONCEPT NUMBER	STRUCTURE CONCEPT	DEPLOYMENT	REFOLD	RELATIVE COST	REMARKS
1.	Single Fold-Rigid guides & conveyors (See Fig.7-1 & 7-2	Guide Rails & Conveyors sequenced by cell fold interlock. Semi-automatic since modules must be inserted in guide rails by EVA or RMS.	Same as Deploy in reverse, plus EVA or mechanization req'd to unlock diag. telescope struts.	1.1	A. Permits deploying structure in any length increment. B. Deployed structure rigidly attached to shuttle. C. Modules may be coupled before or after deployment.
2.	Double fold-rigid guides & conveyors (See Fig. 7-1 & 7-2	Same as 1. After double fold to single fold module operation by EVA or RMS.	Same as 1.	1.2	Same as 1.
3.	Single fold-cranks & push rods. (See Fig. 7-3	Push rod, from long. to linear actuator on fixed strut, cranks long.90°.	Same as deploy in reverse, plus EVA or mechanization required to unlock diag. telescope struts.	1.3	A. Stalling motor or spring drive actuator at end of stroke causes local bending in long. & fixed struts. B. Sliding friction on linear actuator with side load inefficient and prone to binding.

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TABLE 7–1 AUTOMATIC DEPLOYMENT TECHNIQUES STUDY SUMMARY

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CONCEPT NUMBER	STRUCTURE CONCEPT	DEPLOYMENT	REFOLD	RELATIVE COST	REMARKS
4.	Double fold-cranks & push rods (See Fig. 7-3	Sames as 3. Plus push rod from lateral to linear actuator on fixed strut.	Same as 3.	1.4	Same as 3.
5.	Single fold-linear deploy springs on arms. (See Fig. 7-4 & 7-5	Linear spring between 6" arms on two opposed long. approx. parallel to telescope diag., deploy rate controlled by governor on refold cable reel.	Small motor driven cable reel between diagonal corners opposite to deploy spring and telescope diag., end of cable attached to tele-scope lock release.	1.0	A. Spring moment on long. is max. when folded but zero when deployed. B. Fully automatic deploy & refold by energizing cable reel motor. C. 2 deploy springs & cable reels per cell.
6.	Double fold-linear deploy springs on arms. (See Fig.7-4 & 7-5	Same as 5. Plus deploy springs between 6" arms on opposed lateral struts	Same as 5. Plus cable reel between corners in lateral plane	1.1	Same as 5. Except C. (3 deploy springs & cable reels per cell.)
7.	Single fold-torsion deploy springs (See Fig.7-6 & 7-5	Torsion springs on all long. end pivots.	Same as 5.	1.1	A. Deploy moment on spring causes local bending in long. & fixed struts. B. Same as 5. C. Same as 5 D. Large torsion springs exceed folded structure envelope.

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TABLE 7–1 CONTINUED AUTOMATIC DEPLOYMENT TECHNIQUES STUDY SUMMARY

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CONCEPT NUMBER	STRUCTURE CONCEPT	DEPLOYMENT	REFOLD	RELATIVE COST	REMARKS
8.	Double fold-torsion deploy springs (See Fig. 7-6 & 7-5	Same as 7. Plus torsion springs on all lateral strut end pivots	Same as 6.	1.2	Same as 7. Except C. (3 deploy springs & cable reels per cell.)
9.	Biaxial scissors fold - fold springs pull on cables paralleling tension struts (See Fig. 7-7 & 7-8	Cable reel initial stroke with threaded strut joint for final stroke & post tensioning all members.	Linear springs in diag. compression struts pull on cables in parallel with folding tension struts which have knee joint buckling springs.	1.0	A. No actuator bending moments in struts when deployed. B. Fully automatic deploy & refold by reversing actuator motor. C. 1 actuator per 2 cells. D. All deploy & refold parts within folded structure envelope. E. Volume compaction ratio is 3 times that of double fold.
10.	Biaxial scissors fold-fold springs on tens. strut knee joints. (See Fig. 7-7 & 7-8	Same as 9.	Tension strut knee joint buckling springs also fold all tension struts closed.	1.1	Same as 9. A thru E. F. Bending spring rate in folding tension struts results in less positive complete fold.

TABLE 7–1 CONTINUED AUTOMATIC DEPLOYMENT TECHNIQUES STUDY SUMMARY

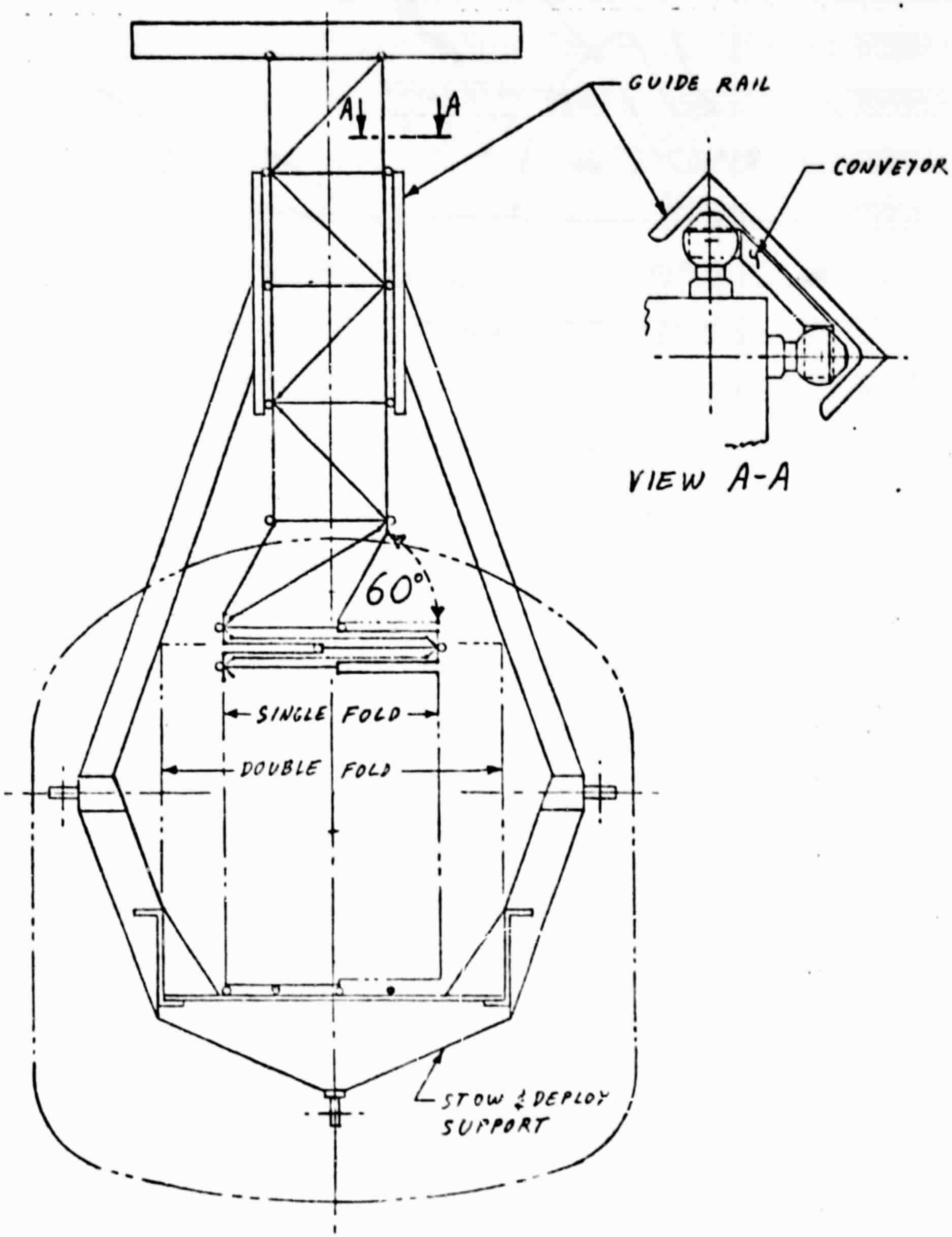

FIGURE 7–1–RIGID GUIDES AND CONVEYORS

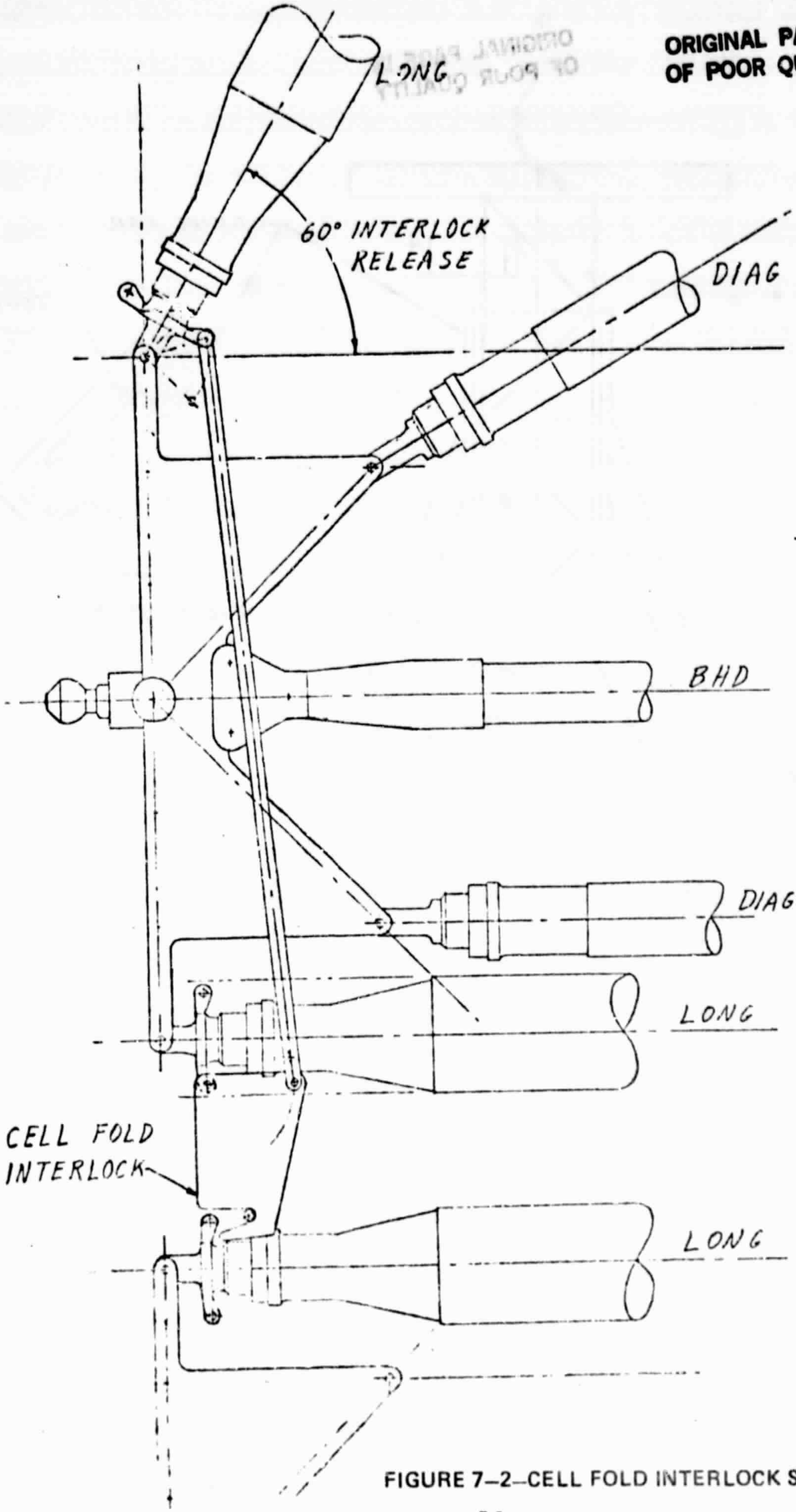

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FIGURE 7–2–CELL FOLD INTERLOCK SEQUENCE

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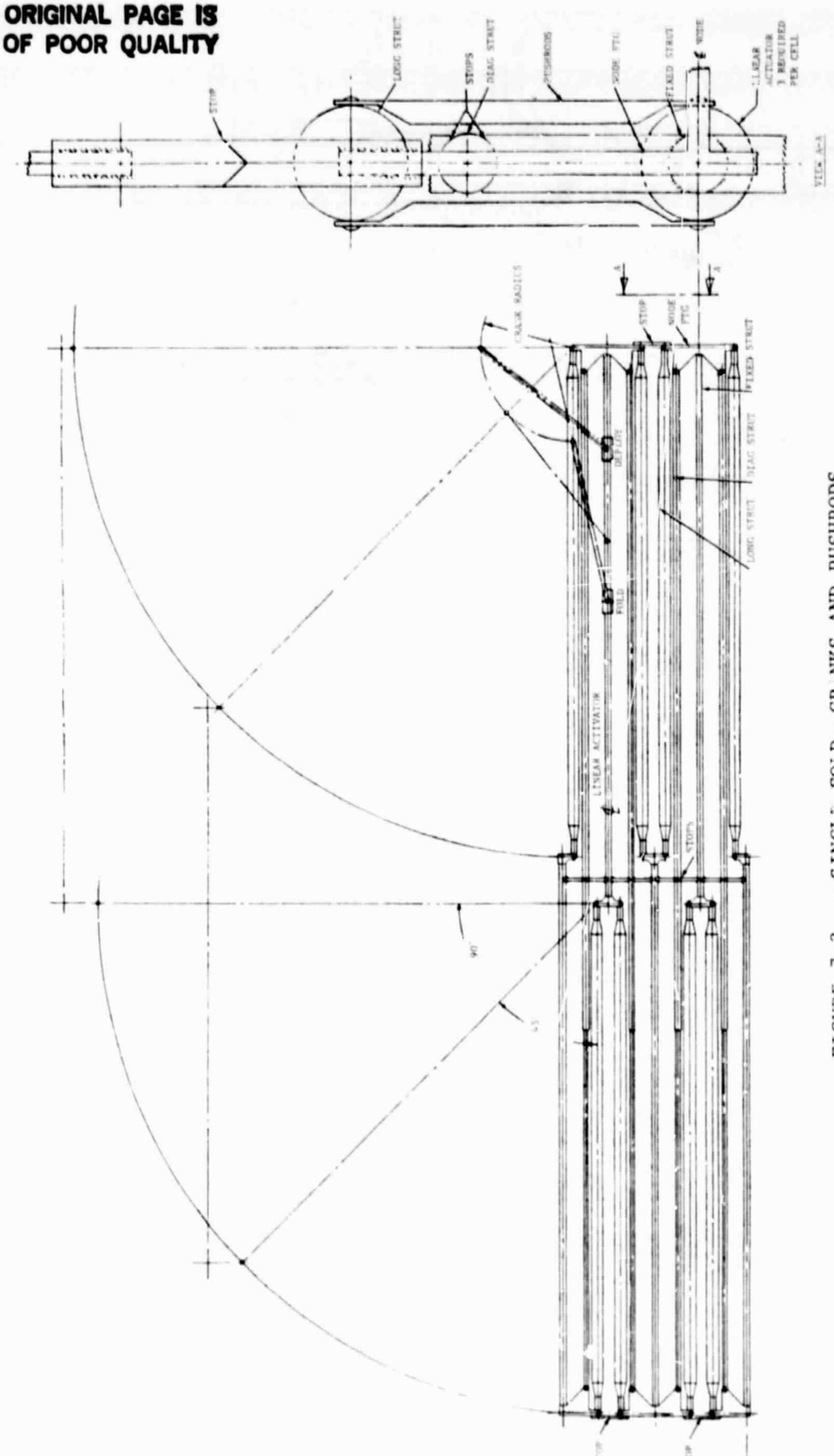

FIGURE 7-3 --SINGLE FOLD--CRANKS AND PUSHRODS

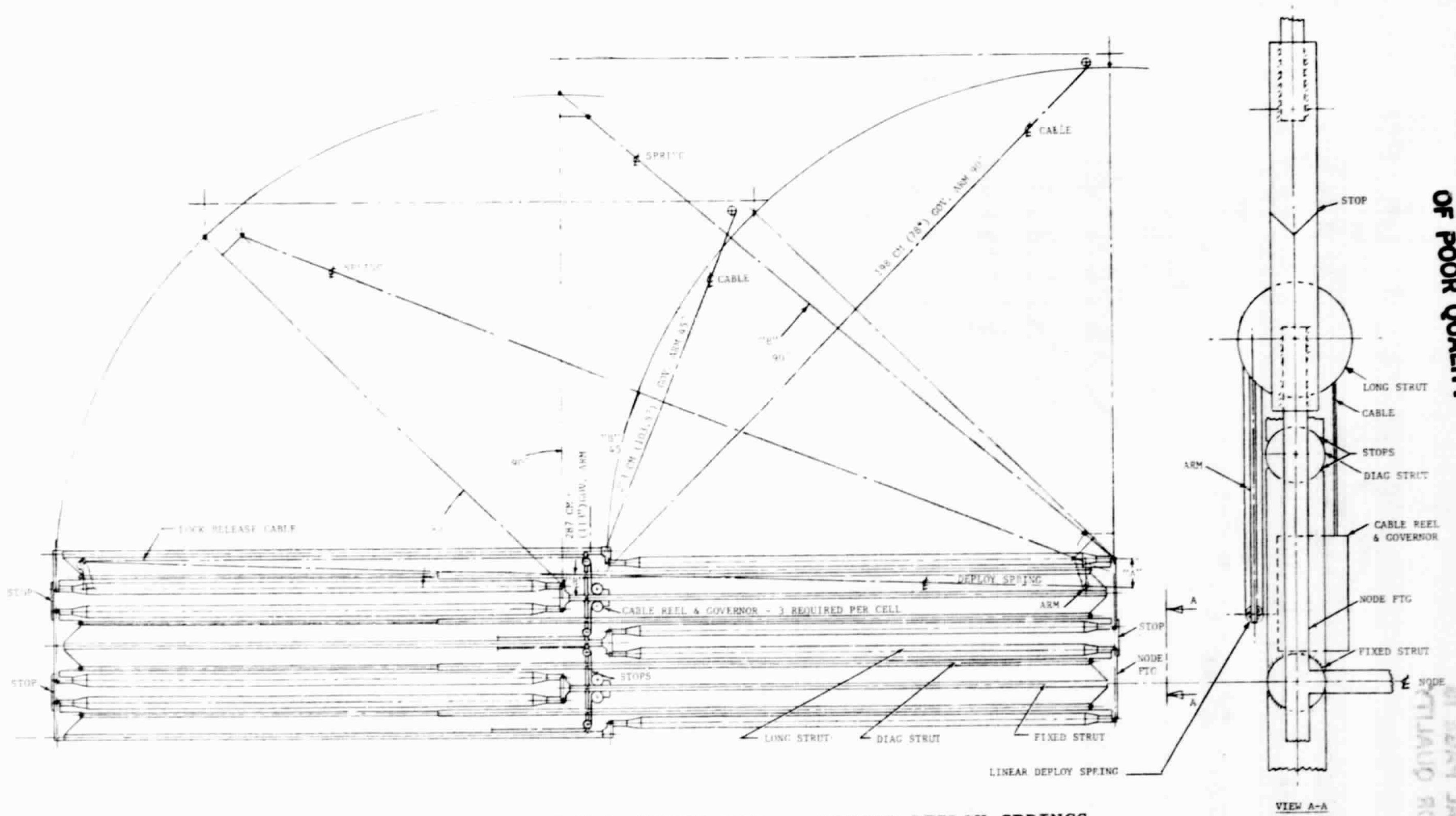

FIGURE 7-4 SINGLE FOLD -- LINEAR DEPLOY SPRINGS

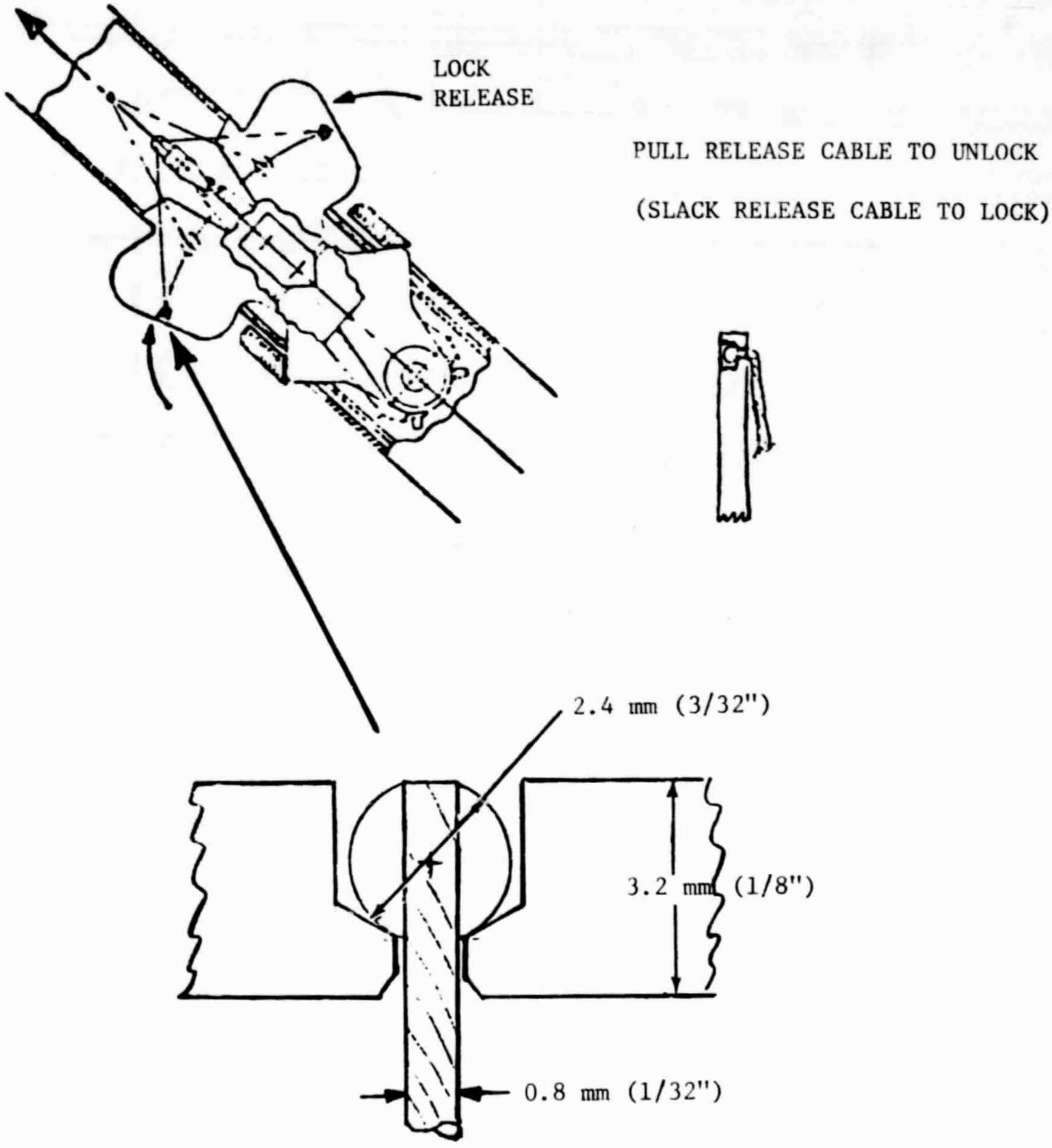

FIGURE 7-5-TELESCOPE LOCK RELEASE

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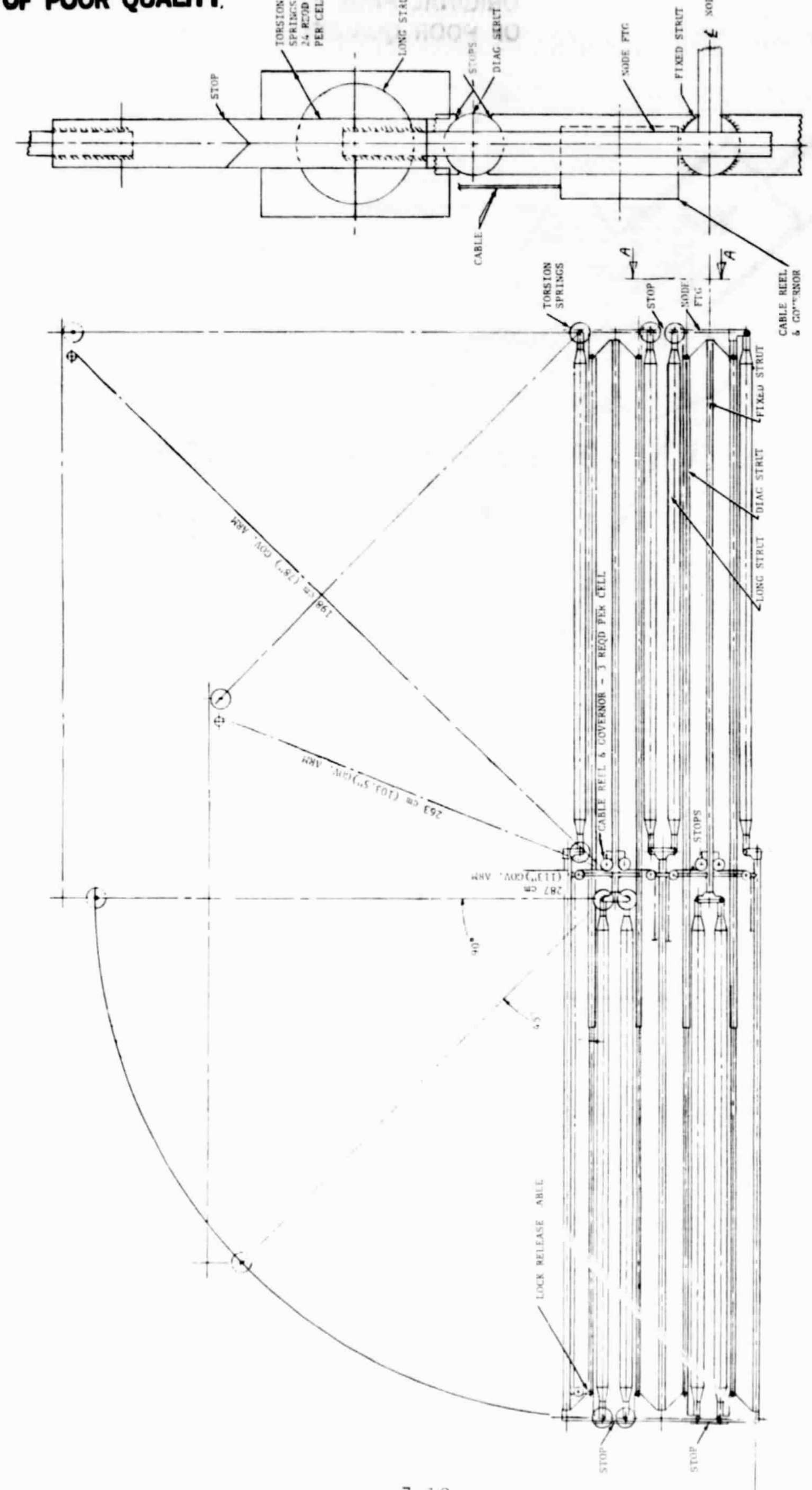
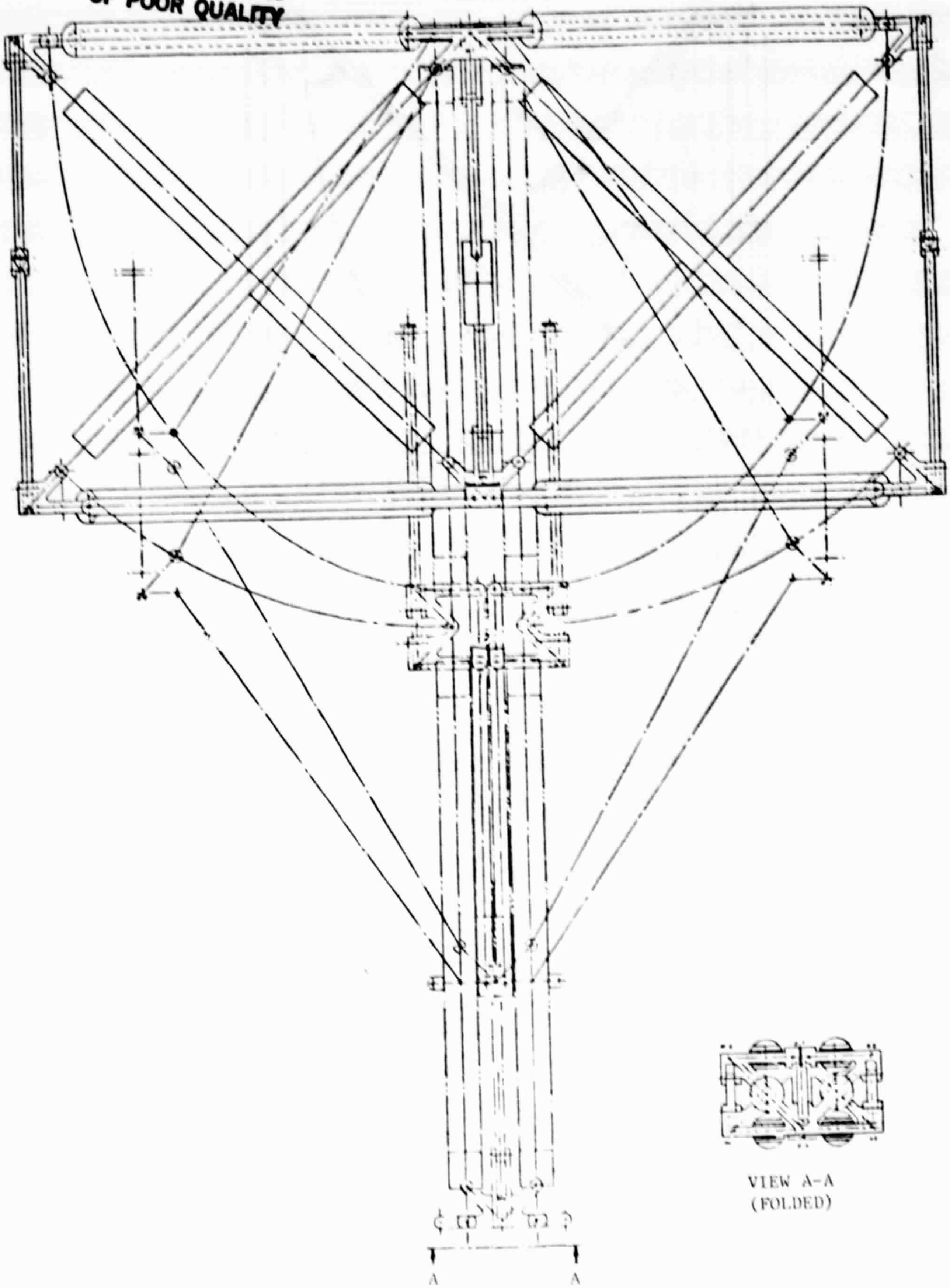


FIGURE 7-6 --SINGLE FOLD--TORSION DEPLOY SPRINGS



VIEW A-A
(FOLDED)

FIGURE 7-7 - BIAXIAL SCISSORS FOLD POST TENSIONED STRUCTURE

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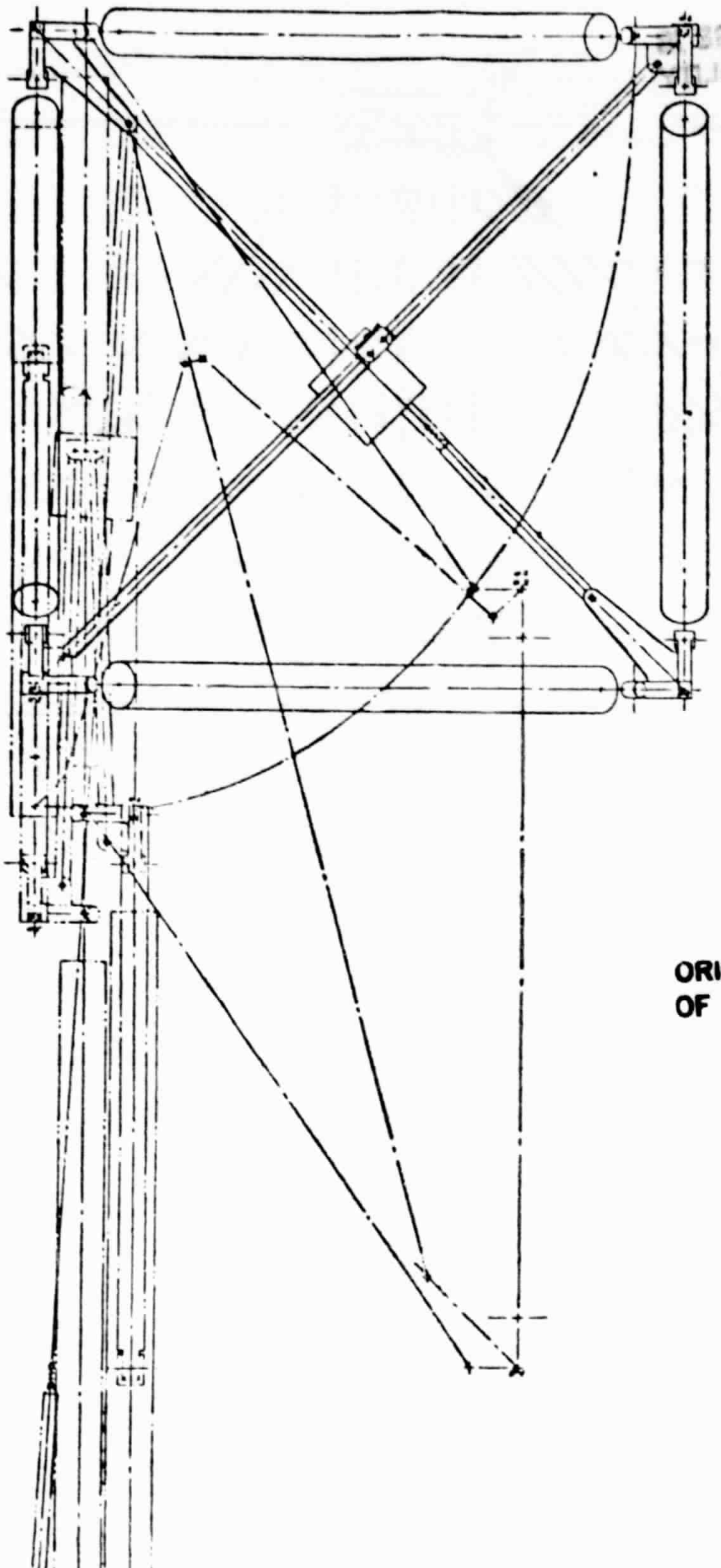

℄ 57M (2 CELLS WIDE)

FIGURE 7-7 - (CONTINUED)

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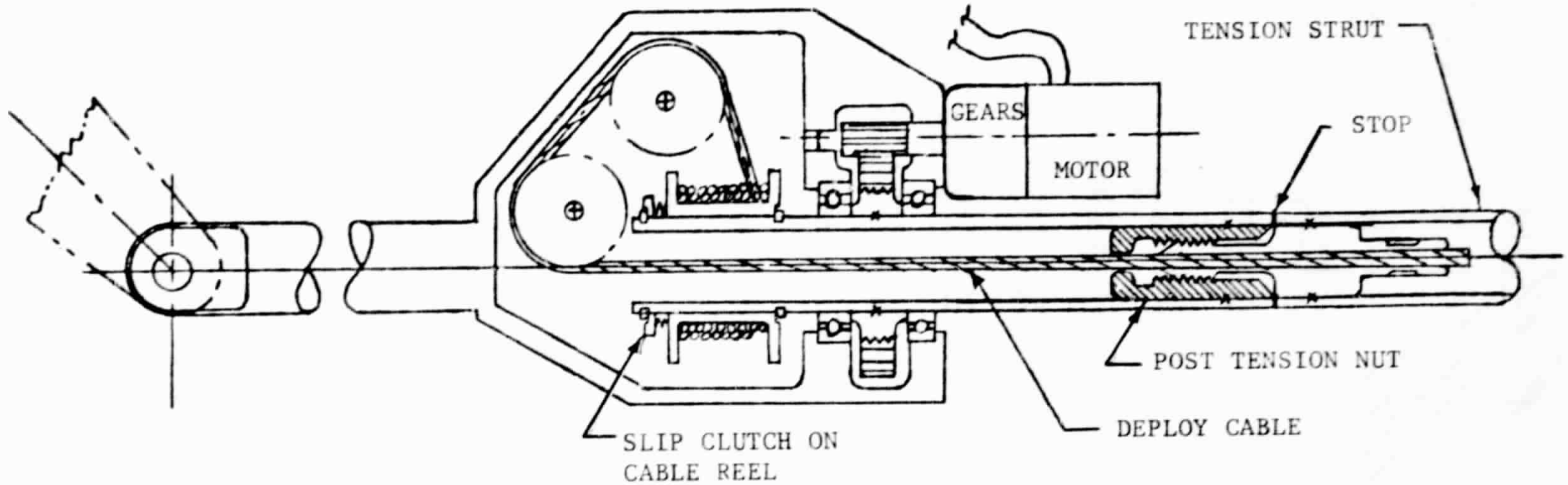

FIGURE 7-8-ACTUATOR-BIAXIAL SCISSORS FOLD POST TENSIONED STRUCTURE

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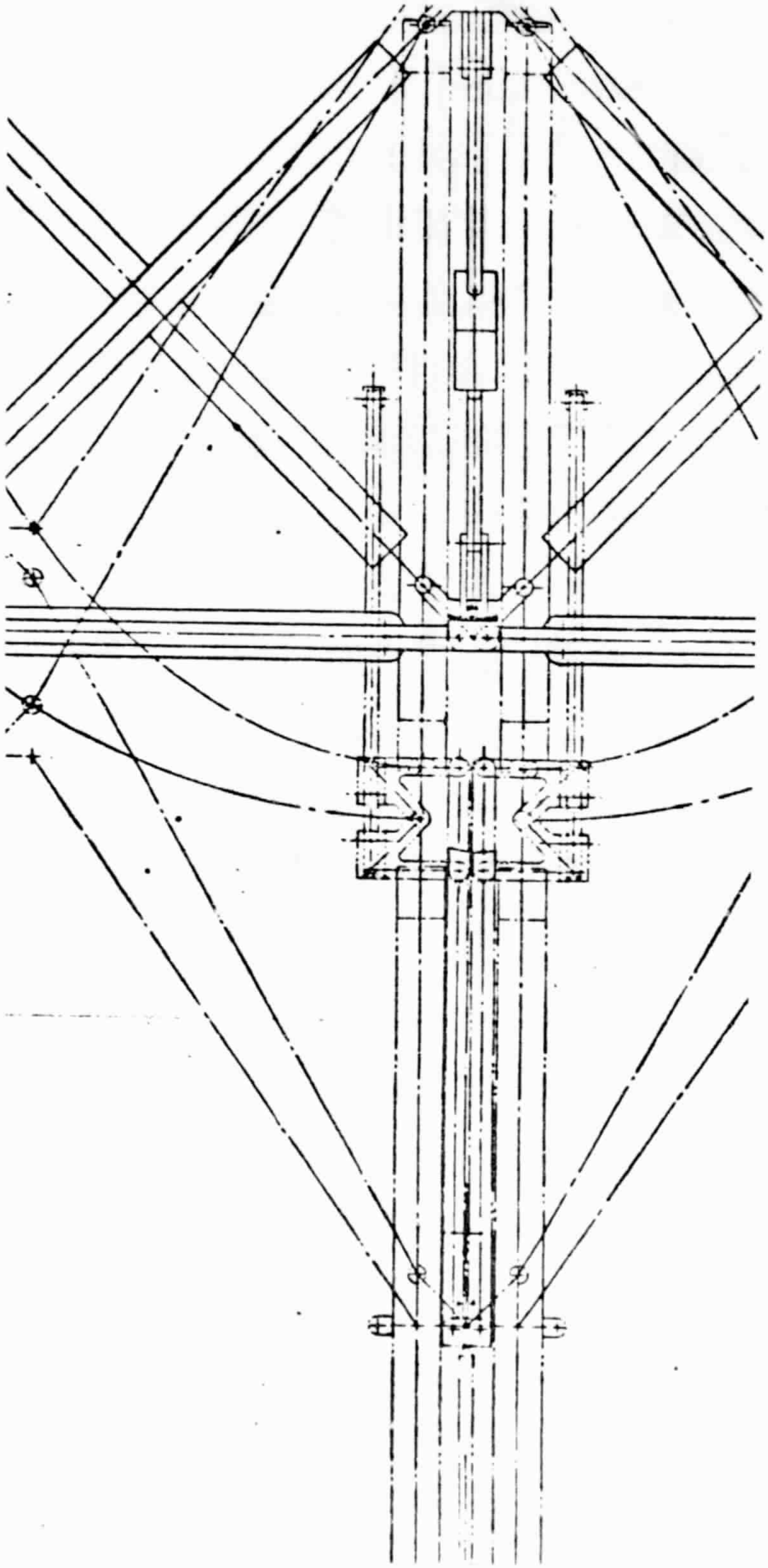

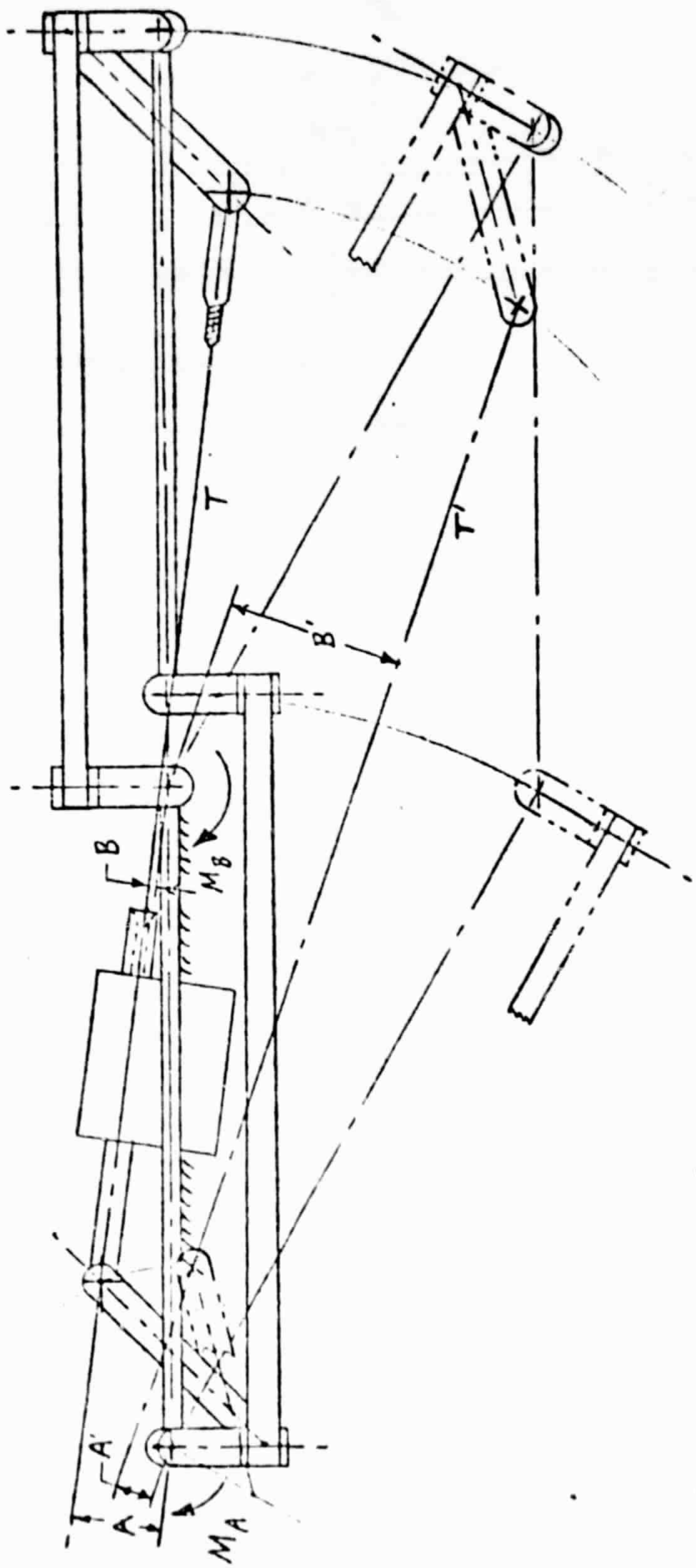

$$M_T = M_A - M_B = T(A-B)$$

$$M_T' = M_A' + M_B' = T'(A'+B')$$

FIGURE 7–9—DEPLOY MOMENTS FOR TWO CELLS OF BIAXIAL SCISSORS FOLD

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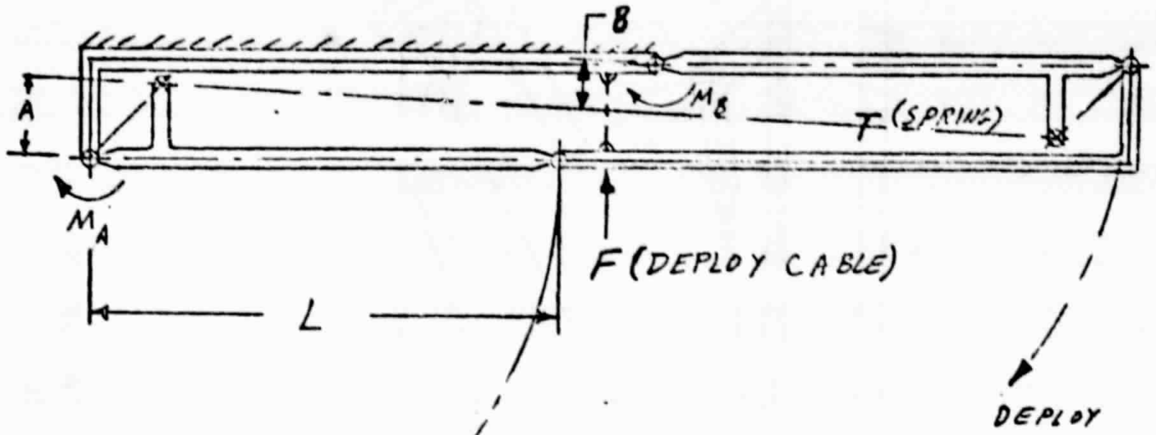

$$F = M_A + M_B / L \quad \text{WHERE} \quad M_A = TA \;\&\; M_B = T.B$$

$$F = T(A+B)/L$$

FIGURE 7–10–DEPLOY FORCES–ASSUMING NO FRICTION
FOR DOUBLE FOLD AT ONE END OF A CELL

o The rate of deployment is controlled by a deployment governor cable connected between the fixed struts (See "F" in Figure 7-10). It operates between diagonal corners of a cell as the corners move apart during deployment.

o One end of the deployment governor cable is wound on a reel which contains a clock escapement type of rate governor. This type governor provides adequate rate control over a wide range of temperature and cable reel torque in a simple, reliable manner. Deployment governor cable tension increases from about 2.22 to 11.2N (0.5 to 2.5 lb_f) during deployment. Deployment time may be varied from minutes to hours as dictated by platform size.

o At the end of deployment the deployment spring tension is reacted by compression in the telescoping struts, which were moving in parallel with it. This provides a positive engagement of the telescope strut stop and lock.

o Deployment in the longitudinal and lateral axes of a wide area platform may be done simultaneously, with rough synchronization provided by the rate governors. Since the structure is very flexible until fully deployed and locked, precise synchronization is not required.

REFOLD (CONCEPT 6)

o If refold is elected, a small 28 VDC motor could be incorporated on each deployment governor cable reel in the rewind direction. One motor per cell face is required. (Less than 2 watts power per motor is required.)

o The other end of the governor cable is routed down the fixed strut and attached to the telescope tube lock as in Figure 7-5.

o After cable slack is wound in and cable tension increases, the telescope strut will be unlocked by initial cable travel.

o Additional rewinding of the governor cable reel will extend the strut, which is the opposite diagonal, and refold the structure against the force of the deployment spring.

o When all the structure cells are fully folded against their stops all rewind motors will stall.

o The cable ties must then be unreeled and wrapped around the structure and secured in the locks. This can be accomplished by EVA while the structure is held by the RMS for restowage in the shuttle cargo bay.

o The refold power wires may then be deenergized and shorted together so that no stray electricity can run the motors.

7.2 Automatic Biaxial Scissor Fold (BASF) Structure (CONCEPT 9)

The most promising automatic concept for the BASF is detailed below. The preferred structural configuration must fold in both axes simultaneously. Modifying the pivot axes would enable sequencing the fold axis operations, but at the expense of more actuators.

This concept was not pursued through the next task (see Section 8), preliminary design, due to the early development stage of the basic structure concept.

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DEPLOYMENT (CONCEPT 9)

o Cable ties around the folded structure are used for restraint as in Concept 6 above.

o Each cable tie is retracted into its reel case so there will be no loose ends to snag deploying structure.

o One actuator for each two cells will begin rotating to wind the deploy cable on the cable reel. See Figure 7-8 - Actuator.

o The deployment cable tension acting on the 3.81 cm (1.50 inch) arm of the node lugs at both ends will provide the initial deployment moments which start opening the structure. See dimension "A" in Figure 7-9.

o Cable tension is limited by a slip clutch on the cable reel providing a constant acceleration to the structure during deployment start up, without stalling the actuator motors.

o When the deployment rate matches the no-slip cable reel speed, all deployment cables will move at the same velocity for the remainder of deployment.

o Since the node lugs are at a 45° angle to the lateral axis a moment will be induced in the node lugs in the longitudinal axis as the structure begins opening in the lateral axis.

o As the structure opens a few degrees the moment arm, dimension "B" in Figure 7-9, will increase in the lateral axis, and "B" will also increase in the longitudinal axis due to the biaxial deployment with the 45° node lugs.

o Near the end of deployment, the post tension nut will be guided by the deploy cable to engage the threaded end of the tension strut. See Figure 7-8-Actuator.

o The cable reel slip clutch now permits slow winding of the deployment cable while the post tensioning nut is screwed onto the end of the tension strut.

o At a predetermined tension, the stop is contacted and stalls the gear motor. All folding members will be in tension and all diagonal struts will be in compression.

o When the motor is de-energized the tension strut will relax a few degrees, permitting the deployment cable reel to slacken. This will also relieve any torque which tends to unscrew the post tension nut.

o The post tension nut will be locked in place by its irreversible thread lead and/or additional locking device.

o The deployment power wires may then be shorted together so that no stray electricity can run the actuators.

REFOLD (CONCEPT 9)

o Reverse polarity will run all deployment actuators in reverse.

o The post tension nuts will back off the threaded end of the tension struts and the cable reels will put more slack into the deployment cables.

o Knee joint buckling springs will start folding all longitudinal and bulkhead diagonal (tension) members inward.

o Linear refold springs in the diagonal compression struts will pull on cables, in parallel with the folding tension members, to completely fold all nodes together, mating the fold stops.

o When the structure has completed about one half of the fold travel, the deployment motors will be de-energized and shorted through a resistor. All actuator motors then act as generators and slow the refold operation to acceptable limits.

o The mechanical advantage of the deployment actuators to the refold springs will reduce as the fold stops are approached. However, this will be offset by the refold springs force reduction, to almost zero, as the fold stops are approached.

o After the refold stops are contacted the restraint cables must be unreeled and wrapped around the structure and secured in the locks. This can be accomplished by EVA while the structure is held by the RMS for restowage in the shuttle cargo bay.

8.0 PRELIMINARY DESIGN OF SELECTED AUTOMATIC DEPLOYMENT STRUCTURE

The Double Fold Structure with fold stops, deployment springs and cable govenors was selected for preliminary design. A wide area platform configuration was chosen for this effort because it not only encompasses all of the characteristics of a beam (arm), but it was expected to finish answering the question of feasibility of deploying wide area structure. This in fact was done in the initial part of the design by establishing that the symmetry (or mirror image) continuity of the structural elements does, in fact, occur in all three axes, and the DFDC concept is good for beams, wide area and/or deep platforms.

Figures 8-1 through 8-4 (Drawing 221-60180) shows eight cells of structure designed to deploy automatically into a small (2 x 4 cell) wide area platform. This configuration has equal diameter lateral and longitudinal struts, while a beam configuration uses smaller diameter (for lower loads) lateral struts.

The aluminum structure shown has 3 meter cells with 63.5 mm dia large struts and 31.8 mm dia diagonals and fixed (vertical) struts. The nodes attach rigidly to the fixed struts and attach by pivots to all other struts. These nodes are basically the same size and design as used for the Neutral Buoyancy Test Structure. Node stops were added where nodes of adjacent cells fold together in a common plane. Additional stops were added to the fixed struts near the nodes which can support the slender extended diagonals passing between them. These stops support the diagonals at mid length (see Section D-D Figure 8-4 for detail). The stop cradles can be made wider, if necessary, to capture the diagonals during folding.

The folded structure is designed to be externally supported on four sides at the four stations shown which are in the planes of the stops. It will also be externally restrained at both ends. All external (launch) support is conceived to be the function of a structural cage surrounding the folded structure. This cage would support the folded structure snugly during handling and shipment and could be attached to the shuttle cargo bay by longeron and keel fittings for launch. When in orbit, the external supports will be backed away from the folded structure and the top of the cage will be hinged open to permit removing the structure with the RMS for deployment.

When the four restraint cables wrapped around the folded structure at the four node stations are released, the structure will begin to deploy in all axes unless a sequencing step for axis by axis deployment is desired. Release initiation could be electrical, if remote, or tripped by RMS or EVA. Detail "B" on Figure 8-2 shows a deployment spring cable routed over sheaves on an arm at one end of each longitudinal and lateral strut. This provides the 6.78 N-m (60 inch lb) starting moment necessary to overcome pivot friction on all the pivoting struts. Pivot friction is primarily due to a light press fit on the NAS 561C6-13 spring pin used in all pivoting strut ends to eliminate joint freeplay. The arm is tilted 2°30' so that the sheave at the outer end will clear the diagonal strut as it passes during deployment. This sheave is geometrically located so that, when fully deployed, the projected deployment cable center line passes through the longitudinal strut end pivot. Thus no end moment remains in the strut to reduce its compression buckling limit load capability.

The deployment cable passes through the deployment spring inside the strut and connects to a spring retainer near the other end of the strut as shown in detail "C", on Figure 8-3, in the deployed position. A spring anchor cable connected to a terminal in the strut end cap also passes through the deployment spring and connects to a second spring retainer at the other end of the spring. When the structure is folded the first spring retainer will be pulled 94 cm (37 inches) by the deployment cable to compress the spring to its maximum load of 31.14 N (7 lbs). The spring retainer and spring coils slide inside an antibuckle sleeve which reduces friction and protects the strut wall from chaffing by the spring. Without a sleeve, the long spring in compression will have numerous buckles that are limited by contact with the cables passing through the spring. It was estimated that the cable friction caused by spring buckling would require that the spring force (and weight) be increased about 30% to maintain the required deployment forces.

A design for precise vernier adjustment of strut length from one end cap is also shown in detail "C" on Figure 8-3. This is necessary if adjustment is required, since the other strut end cap must be fixed to maintain alignment of the torque arm with the pivot lug and cable.

There is one deployment cable with two springs, one at each end of the cable, for each longitudinal or lateral cell face in the wide area platform structure. The springs are enclosed in 2 of the large diameter struts which have torque arms. In addition there is one double length deployment spring inside each trunnion mounted telescoping diagonal strut for each upper or lower cell face in the structure. The latter springs are used to provide 13.3 N (3 lbs) compression in the trunnion diagonals at full deployment to insure that the telescope stops and locks are engaged. On the longitudinal and lateral faces the deployment cables are always approximately parallel to the telescope diagonal struts and provide 13.3 N(3 lbs) compression, to insure that their stops and locks are engaged at full deployment. Since the trunnion ended diagonals deploy when either the longitudinal or lateral struts unfold, no torque arms are needed to begin their deployment.

Deployment rate is controlled by a cable reel and governor on each longitudinal and lateral cell face of the structure. Detail "E" on Figure 8-3 shows the design details. The reel spool is 1.91 cm (0.75 inch) diameter with 5.33 cm (2.10 inch) diameter end plates and the groove is only wide enough, .170 cm (.067 inch), for two cable diameters. 406.4 cm (160 inches) of .079 cm (1/32 inch) cable will wind on this reel in 36 turns with no level wind required. A clock or timer escapement mechanism controls the reel unwind velocity during deployment through a one way clutch. A low torque rewind spring will wind the governor cable on the reel and maintain .22 to .44 N (0.05 to 0.10 lbs) tension in the cable when fully wound. This spring insures that the governor cable is taut and yet free to unwind when 2.22 to 11.1 N (0.5 to 2.5 lbs) tension is applied during deployment. The larger cable reel diameter at initiation of deployment provides a higher starting torque to get the escapement governor running and also permits an initial deployment rate higher than the final deployment rate. The final rate will be limited by the dynamics of stop and lock engagement on the telescoping diagonal struts. The total deployment time for a large wide area platform should probably be between one and two hours.

The 25.4 x 25.4 cm (10 x 10 inch) cross section per folded cell, as shown in Section D-D of Figure 8-1 , is the same as for the node used in the neutral buoyancy test structure which required flotation chambers around the

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small struts. Without flotation chambers this structure can be folded to 20.3 x 20.3 xm (8 x 8 inch) cross section per cell as shown in Figure 8-5. With this 20.3 x 20.3 cm per cell folded section a 14 x 14 cell wide area platform using 3 meter cells will fold into a package 2.9 m square x 8.7 m long. This is the maximum size, of this point design, that can fit in the Orbiter cross section. This package with its structural support will require approximately one half of the Shuttle cargo bay. When the folded structure is automatically deployed it will form a 42 x 42 m platform, 3 m deep with 6.35 cm dia longitudinal and lateral struts and 3.18 cm dia diagonal and vertical struts. This deployed 196 cell structure, shown in Figure 8-6, would weigh about 6,405 Kg (14,141 pounds) of which the automatic deployment mechanization is about 463 Kg (1,022 pounds). 72.5 Kg (160 pounds) of the structure weight is due to the probes on all nodes which form a 3 m square grid pattern on both faces and all four edges of the wide area platform. Four of these probes on the corners of any external 3 m cell face will couple to four drogues on an equipment package or experiment. Thirty of these probes on one edge of the platform will couple to thirty drogues on a second platform to double the size. There is no weight for integral wire harnesses included in this estimate. However, there is sufficient clearance in the folded structure at the nodes to permit routing integral wire harnesses throughout the structure. The additional weight to add wire harnesses would be more than wires and their supports since some deployment spring force, and therefore weight, would be added to flex the wires.

This structure may be automatically refolded if a small 28 VDC torque motor is added to each of the 420 governor cable reels. A power wire harness would be required to connect all the motors to a common power supply. Less than 2 watts power per motor would be required. Refer to paragraph 7.1 for a complete description of automatic deployment and refold sequences of operations for the Concept 6 double fold structure.

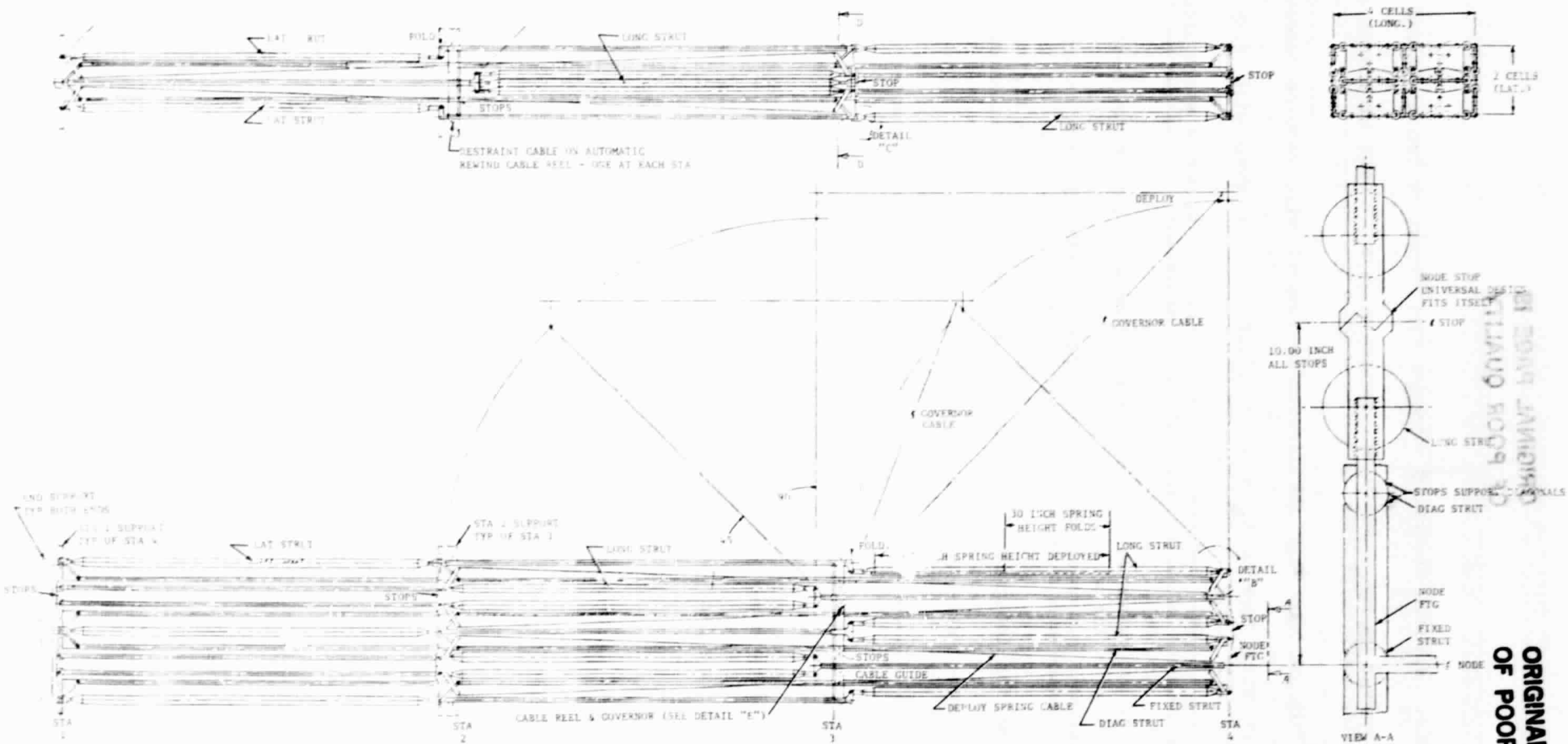

FIGURE 8-1 DOUBLE FOLD STRUCTURE WITH FOLD STOPS, DEPLOY SPRINGS AND CABLE GOVERNORS

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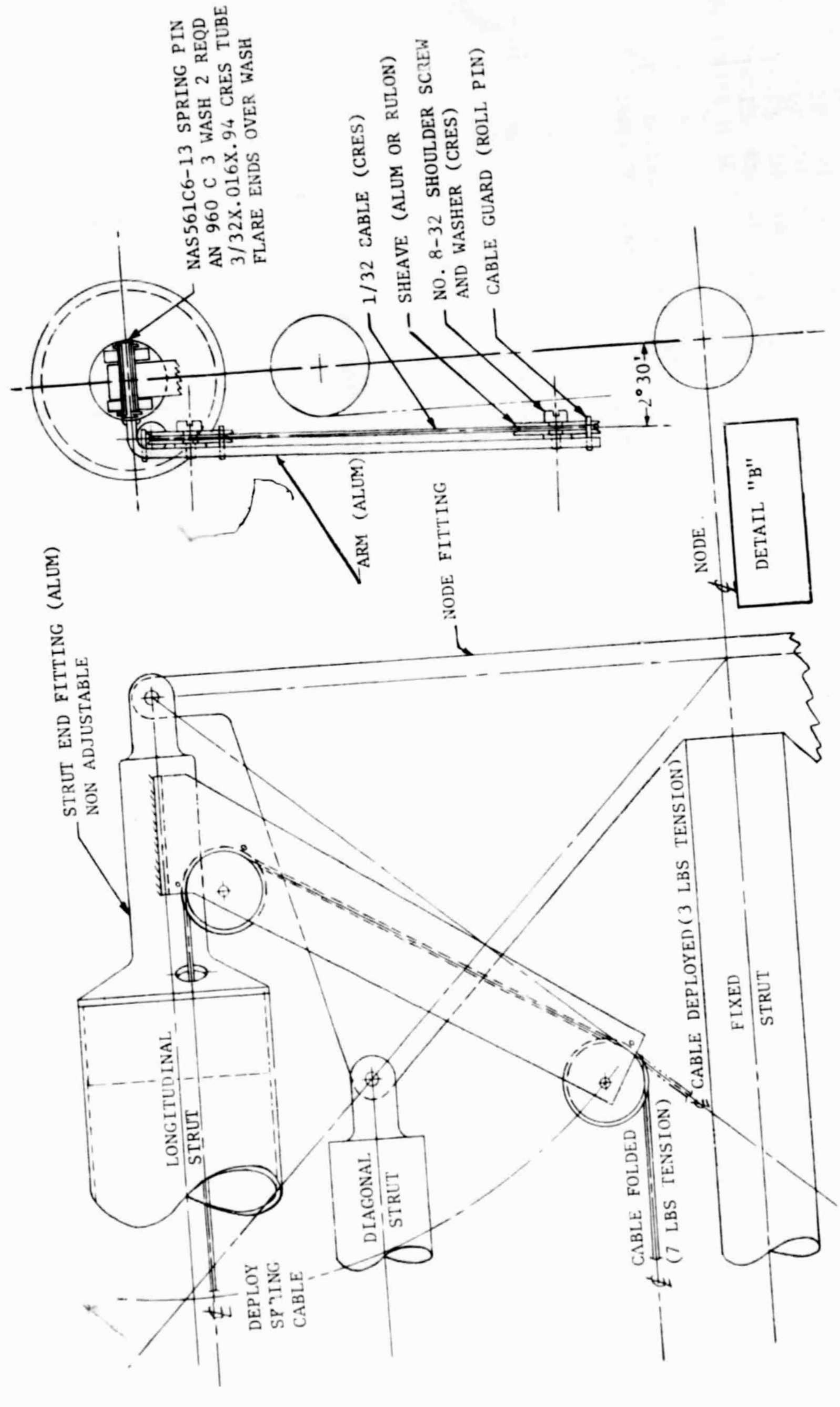

FIGURE 8-2 DOUBLE FOLD STRUCTURE WITH FOLD STOPS, DEPLOY SPRINGS AND CABLE GOVERNORS

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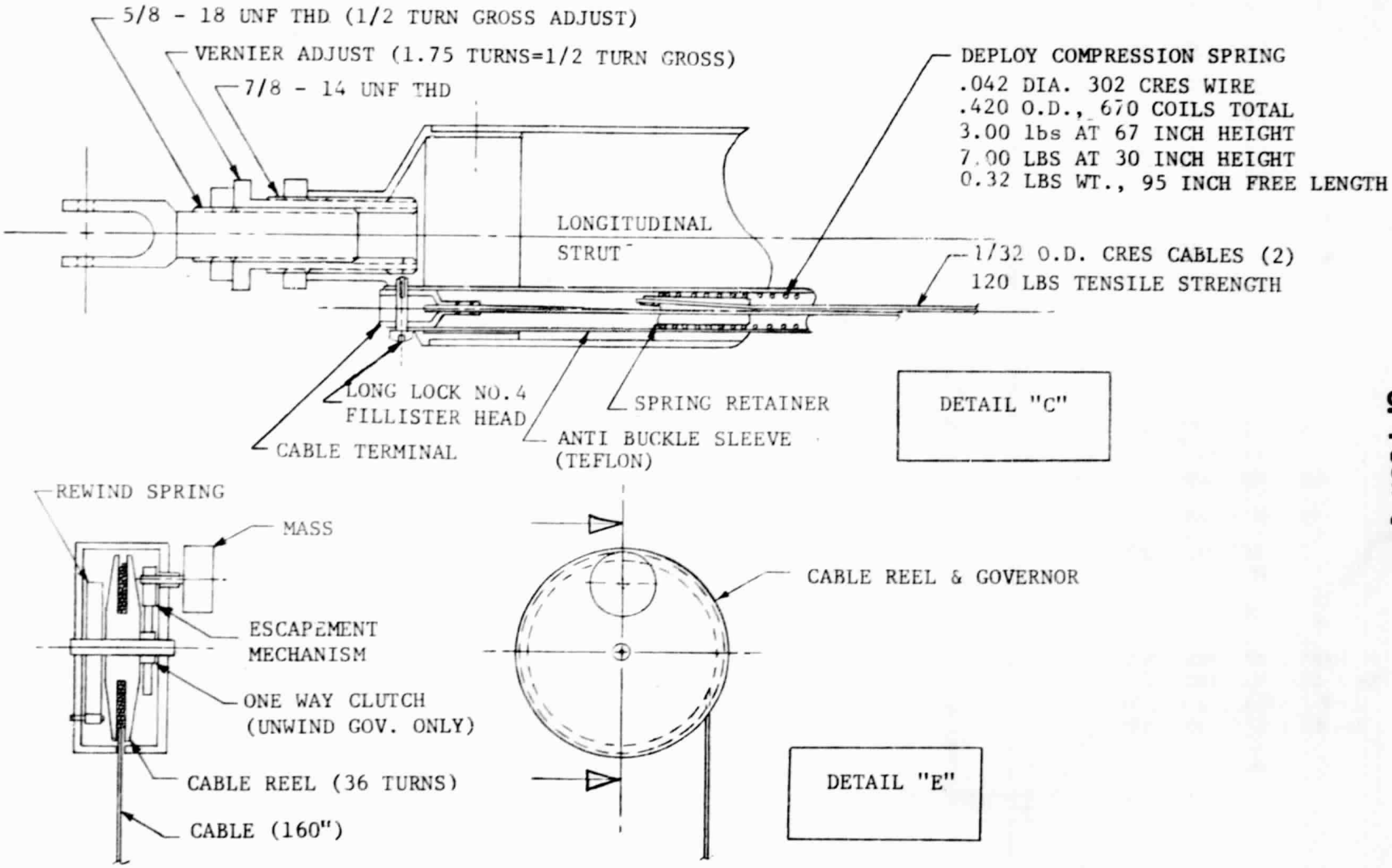

FIGURE 8-3 DOUBLE FOLD STRUCTURE WITH FOLD STOPS, DEPLOY SPRINGS AND CABLE GOVERNORS

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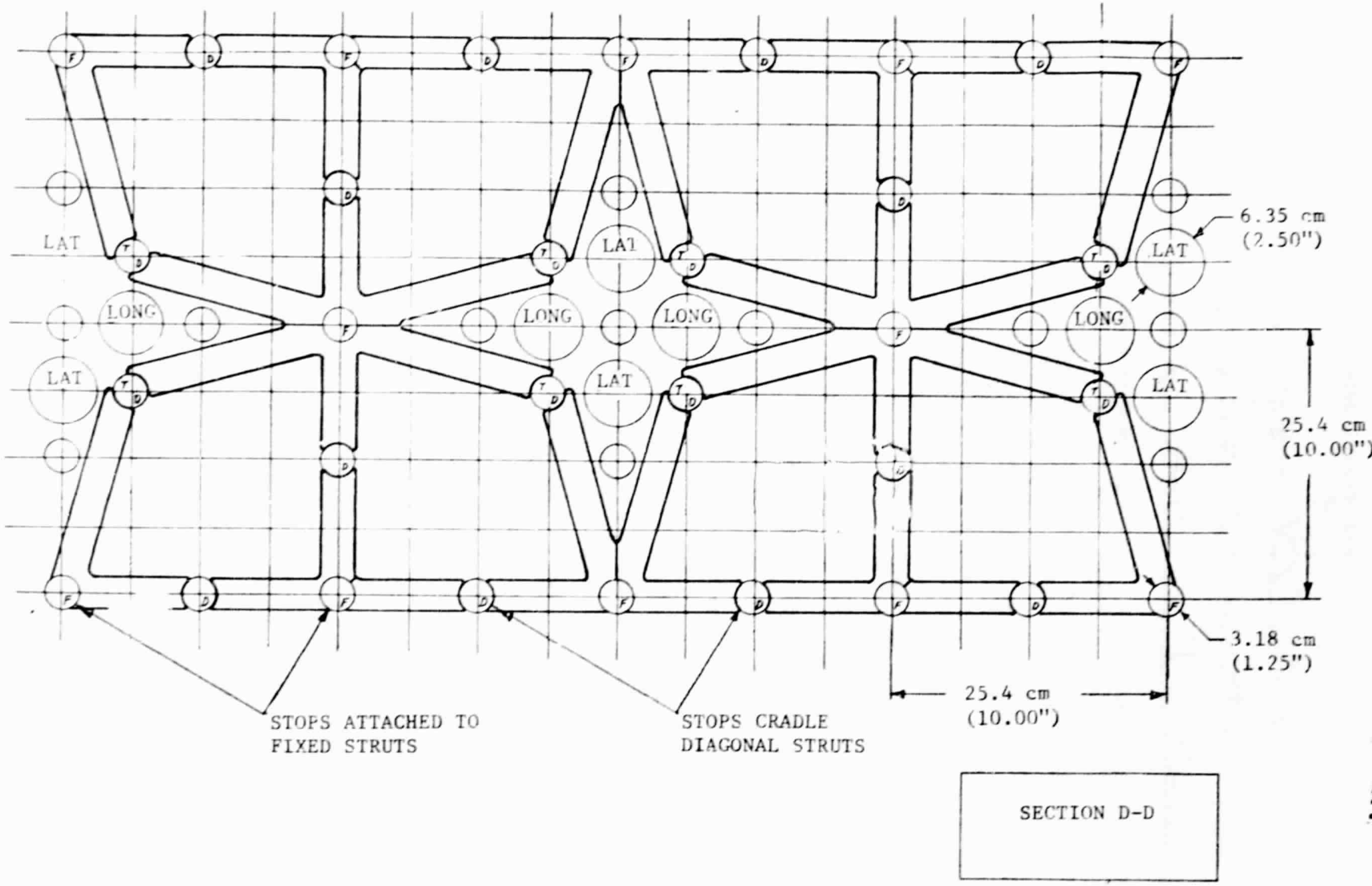

FIGURE 8-4 DOUBLE FOLD STRUCTURE WITH FOLD STOPS, DEPLOY SPRINGS AND CABLE GOVERNORS

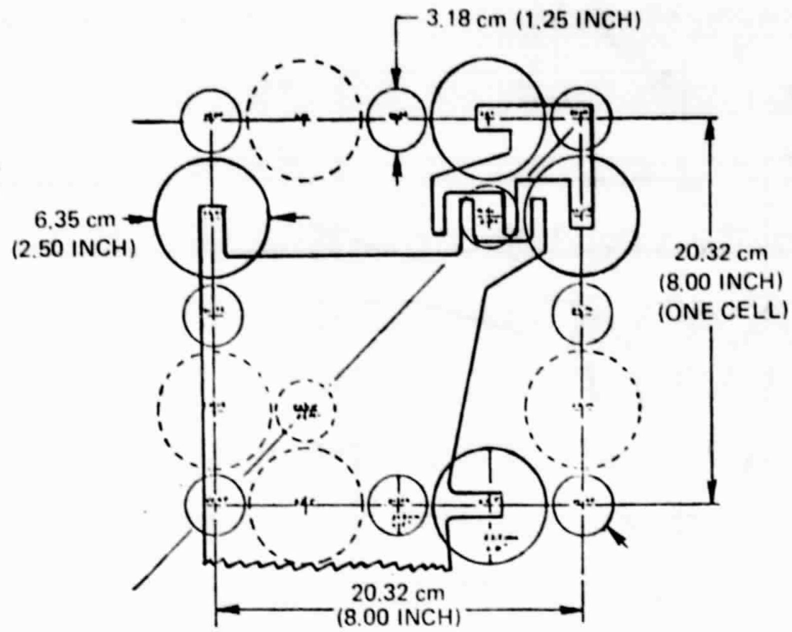

FIGURE 8-5 MINIMUM FOLDED CELL SECTION WITH WIDE AREA PLATFORM STRUTS

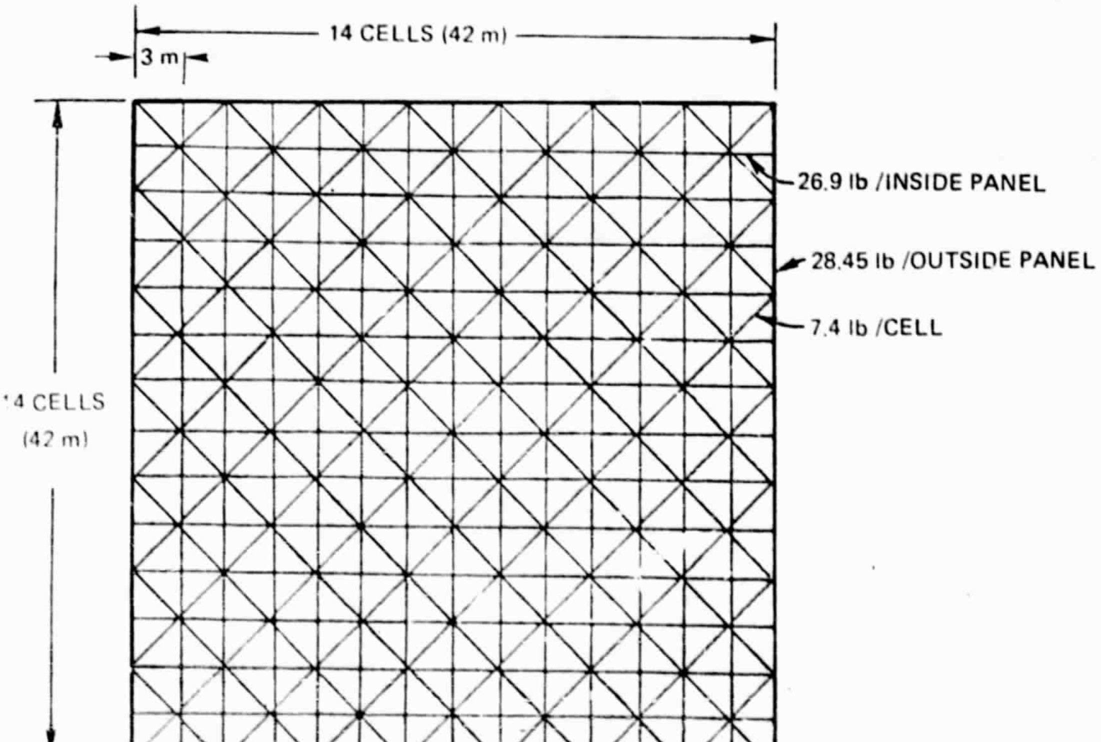

FIGURE 8-6 196 CELL AUTOMATICALLY DEPLOYED WIDE AREA DOUBLE FOLD STRUCTURE

9.0 CONCLUSIONS & RECOMMENDATIONS

The primary effort of this contract follow-on, culminating in the NBS testing, was considered highly successful. While more insight was gained into design requirements and planning for space structure operations, no significant surprises occurred.

The add-on studies for automated deployment show the DFDC structure to be viable with full automation without external power and retractable if desired with low power input. Also, the study shows the structure to be extendable in three axes for deploying either beams, wide area or deep platforms.

CONCLUSIONS

- o Double Fold-Double Cell (DFDC) Structure viable for Space Platform/arm
- o Rigid stops and supports should be built into the folded structure.
- o RMS/EVA capabilities complimentary to each other.
- o Suport structure should have smooth faces to avoid installation snags.
- o Locking devices should be color coded.
- o Interconnect not cost-weight effective.
- o RMS/module interface needs improvement.
- o Deployable much preferred over erectable.

RECOMMENDATIONS

- o Pursue Vought developed Biaxial Scissors fold structure. Compared to double fold structure:
  - 3/1 improvement in packaging volume
  - Fewer actuators required for automatic deployment
  - Post tensioning eliminates freeplay
- o Conduct duplicate NBS and orbital operation experiment for exact correlation and improved prediction capability.
- o Continue hysteresis investigation to enable quantitative analysis and prediction.
- o Update structure size to latest SASP requirements, 1-1/2 meter arms. (see Ref. (8)).
- o Pursue Automated Deployment -
  - Further design & development
  - Automated models
  - NBS Testing
- o Improve ground handling (1-g).
- o Analyze flight (launch) loads.
- o Use NBS for pre-flight training.
- o Obtain by research or development a paint system to withstand NBS environment.
- o Establish on-orbit paint requirements.
- o Further study needed on cable/spring deployment system to assess risk or inconvenience caused by exposed cables.

MFS-25647

APPENDIX I

QUICK LOOK TEST REPORT

NB-37

ERECTABLE CONCEPTS FOR LARGE SPACE SYSTEMS TECHNOLOGY

TEST PERIOD: 9 September - 8 October, 1980

PERSONNEL:

Subjects - Agan (Vought), Hall, Lide, Noneman, Rodriquez (MSFC), Shields (Essex)
RMS Operators - Drinkard (MSFC), Henderson (Essex)
Test Conductors - Loughead, Shields (Essex), Stokes (MSFC)

OBJECTIVES:

1) Evaluation of erectable, deployable concepts for Large Space Structure Assembly via RMS and EVA

2) Compilation of task and subtask times for EVA and RMS assembly techniques

3) Evaluation of stowage and deployment frame concepts for Large Space Structures.

NB-37 TEST APPARATUS

- Two double cell modules, each capable of either single- or double-fold operation. Module-to-module couplers were supplied to join the modules together.

- Three cardtable legs and two single members with end connections. The cardtable legs were attached to the double cell modules and, together with the single members, formed a module-to-module interconnect.

- Payload bay support fixture. This fixture was attached to pallets in the payload bay mockup and supported the test components in the stowed position. The fixture was also adapted to serve as a transportation and handling fixture.

- Each cell was 3x3x3 meters, with each module being 6x3x3 meters and the completed structure with interconnects being 15x3x3 meters.

Figure 1 shows the deployed structure in the NBS.

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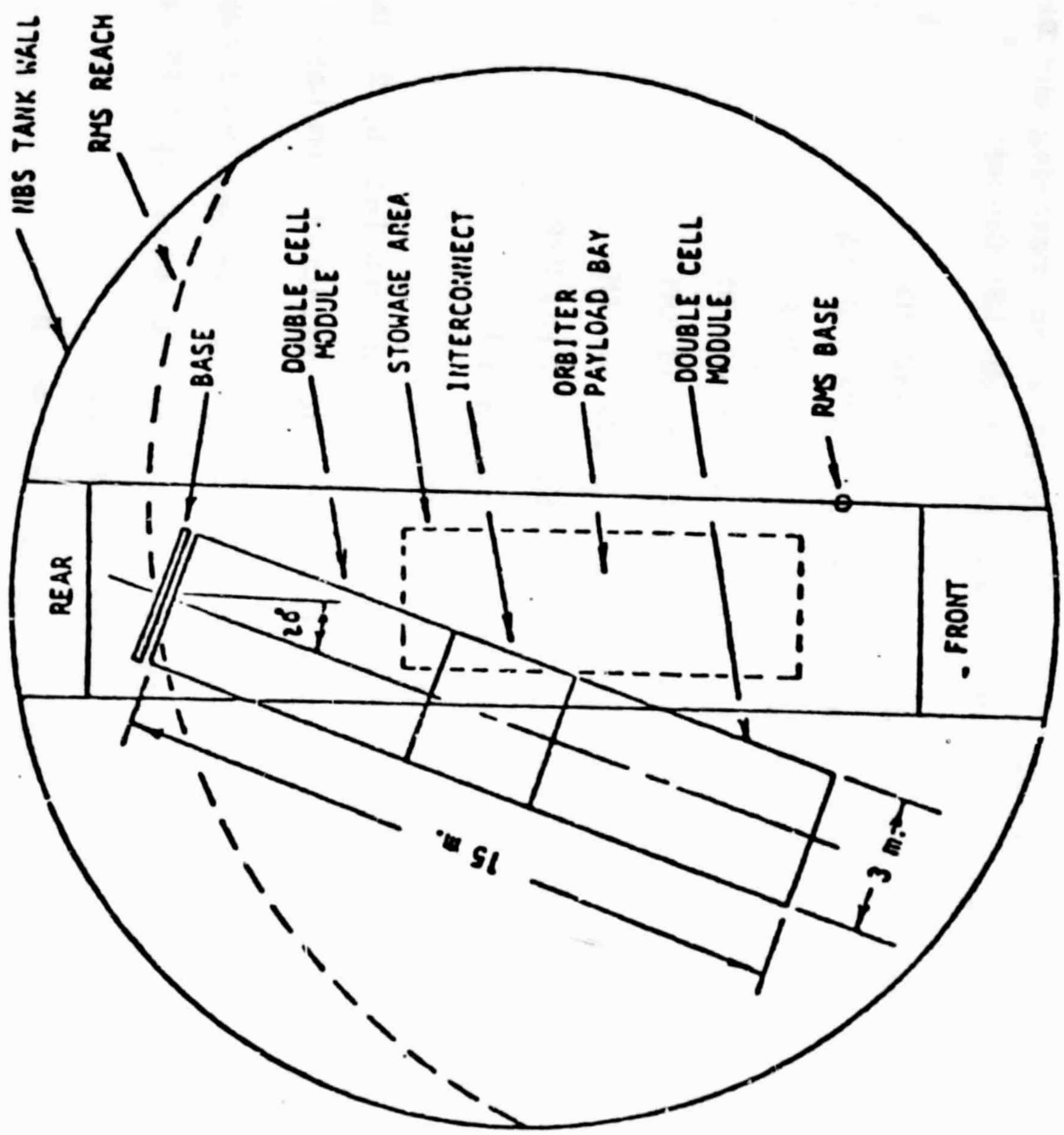

FIGURE 1: TYPICAL TEST LAYOUT IN NEUTRAL BUOYANCY SIMULATOR

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NB-37 TEST PROCEDURES

19 Proposed Tests Involving Various Approaches for Unstowing and Deploying, and Retracting and Stowing the Vought LSS Concept

1. 2 single folds deployed from base by 2 EVA and RMS
2. 2 single folds deployed from orbiter by 2 EVA and RMS
3. 1 single fold deployed from base by 2 EVA and RMS
4. 2 single folds retracted from base by 2 EVA and RMS
5. 2 single folds deployed from base by 1 EVA and RMS
6. 2 single folds retracted from base by 1 EVA and RMS
7. 2 single folds deployed from orbiter by 1 EVA and RMS
8. 1 single fold deployed from base by 1 EVA and RMS
9. 1 single fold deployed from base by RMS only
10. 2 double folds, 1st deployed from orbiter, 2nd from 1st, by 2 EVA and RMS
11. 2 double folds, 2nd retracted from 1st, 1st retracted from base, by 2 EVA and RMS
12. 2 double folds, 1st deployed from orbiter, 2nd from base by 1 EVA and RMS
13. 2 double folds, 2nd retracted from 1st, 1st from base, by 1 EVA and RMS
14. 1 double fold deployed from base by RMS only
15. 1 double fold deployed from base by 2 EVA and RMS

NB-37 TEST PROCEDURES (Continued)

16. 1 double fold deployed from base by 1 EVA and RMS

17. 2 single folds with interconnect, 1st deployed from orbiter, 2nd from 1st, by 2 EVA and RMS

18. 2 single folds with interconnect, 2nd retracted from 1st, 1st from base, by 2 EVA and RMS

19. 2 single folds with interconnect, 1st deployed from orbiter, 2nd from 1st, by 1 EVA and RMS.

Due to hardware and support complexities, Tests 3, 9, 14 and 19 were deleted from the test plan. All other tests were run at least once. Reasons for eliminating these tests were:

- o Completed structure was too long to be deployed up from the orbiter, and

- o Toggle switch control of the RMS did not provide enough control to mate the drogues and probes without EVA assistance.

A total of 15 NBS sessions were conducted with a total of 24 tests completed. Six male subjects participated in testing.

NB-37 TEST PROCEDURES (Continued)

The first three trials involved scuba swim throughs with all six subjects working in teams of two. This was done to validate for neutral buoyancy testing the engineering concepts behind stowage, deployment and retraction. All other trials were run with one or two suited subjects according to the test plan.

Trials varied according to the following conditions:

- o Stowed configuration of structure
  - Single fold in stowage rack
  - Double fold in stowage rack
- o EVA support
  - 1 EVA subject
  - 2 EVA subjects
- o Structure to be deployed/erected
  - Single - double cell structure (6 m)
  - Two - double cell structures (12 m)
  - Two - double cell structures with interconnect (15 m)
- o RMS support
  - RMS with EVA
  - EVA only
  - RMS only - eliminated due to control complexities.

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NB-37 TEST RESULTS AND RECOMMENDATIONS

The results and recommendations are presented for major subsystems involved in all phases of the tests rather than for individual tests, since some tests were conducted only once and there appear to be generalized recommendations based on observations of the entire test series.

- Stowage/Restraint Rack
  - Openings in the sides of the stowage rack allowed structure probes to be inadvertently trapped, making deployment difficult. Sides of rack should be solid.
  - Stowage locks for the structure could not be mated to two probes simultaneously from a single action performed from the EVA work station. Evaluate other lock down concepts of alignment aids.
- EVA, Work Stations/Aids
  - Current work station locations at the aft end of the stowage rack were too low with regard to locking mechanisms, and too distant from locking couplers to permit easy stow/unstow. Move work stations to midline port and starboard sides.
  - Work stations on the deployment frame did not have foot restraints, or sufficient hand holds/tether points. Install hand rails and tether points along top sill of frame, bottom sill of frame, and foot restraints at base of frame.
  - Rearming the LSS locking drogues proved difficult for two reasons. One, the arming spoons were removed for safety reasons, and two, the bottom of the deployment frame did not permit easy access to the drogues. Redesign spoons with longer (6 in.) handles and reinstall them on drogues with protected restraint wires.

NB-37 TEST RESULTS AND RECOMMENDATIONS (Continued)

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- LSS Concept Design

  - While stowed or during translations, the structure was restrained in its stowed configuration with straps. During simulation, velcro straps were used and they proved to be inconvenient to put on or take off. The on-structure restraint system should be redesigned to provide quick connect and disconnect, and there should be provisions for stowing the restraint system after it has been removed from the structure.
  - The "card table" interconnects were designed so that each connection could be made independently of any other. This, however, also enabled the interconnects to "float" independently. Provisions should be made to support the interconnects in the approximate orientation required for proper mating of the structures.
  - The utility cables employed in the simulation did not appear to interfere with any of the operations, but they were only small sections of the utilities. This finding may not hold for full cable routing.
  - The locking wings of the structure did not always engage during structure erection, which could be related to the lock design or to the corrosion inherent in underwater simulations. Additionally, positive lock indication could not be visually determined. Investigate lock design and corrosion buildup on test article and color code positive lock on the lock wings and diagonals of the structure.

C-2

NB-37 TEST RESULTS AND RECOMMENDATIONS (Continued)

- **RMS/End Effector Design and Operation**

  - The existing control concept for the RMS is not a flight concept. Currently, control is through toggle switches which are normally operated one at a time and, consequently, provide joint-by-joint stepping movements. Changes to the control concept should be made to permit integrated RMS movements based on the desired or commanded tip position.

  - The opposed jaw end effector was troubled with actuation and alignment problems during the tests, and suggested modifications to the jaw seemed to work well until operating forces broke the special adapter. Opposed jaw end effectors, while popular, are not recommended for tasks involving 6 DOF tasks due to rotational forces exerted on the jaws, which result in bending the jaws. Other end effectors should be considered such as alternately opposed five finger effectors, or hemi-tube extended effectors.

- **Roles**

  - The task sequences for this LSS assembly were defined, but the roles and responsibilities for specific operations could not be determined until several simulations were completed. Dexterous tasks such as lock, unlock, fine guide, mate probes and drogues were better done by EVA. Gross transportation and orientation of structures can best be accomplished by RMS operations. The transition points for RMS control appear, conveniently enough, to be at points when the EVA crew does not have physical contact with the structure.

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APPENDIX II

RANGE AND MEAN TIME TO PERFORM REPRESENTATIVE TASKS INVOLVED IN ERECTING LARGE SPACE STRUCTURES

DATA DERIVED FROM NB-37

	TASK DESCRIPTION	(T = Sec) RANGE	(T = Sec) MEAN	TASK SIZE (N)
1.	RMS orient & grasp target using opposed jaw effector & from various and uncontrolled start locations	29 - 252	128	27
2.	RMS remove a module from storage & rotate it 90°	84 - 561	194	12
3.	RMS transport and orient a module to aft frame or first module	130 - 320	224	10
4.	RMS/EVA orient a module for lock on	24 - 202	124	6
5.	EVA lock up all four drogues	58 - 198	105	11
6.	Deploy Cells A Module 1, Cell 1	80 - 192	135	5
	B Module 1, Cell 2	81 - 126	96	5
	C Module 2, Cell 1	124 - 318	207	6
	D Module 2, Cell 2	92 - 135	127	6
7.	Install interconnects & deploy	72	-	1
8.	EVA unlock diagonal wing locks in preparation to stow	14 - 57	28	9
9.	Collapse cells for stowage:			
	Cell 2 (First cell collapsed)	28 - 130	65	4
	Cell 1 (Second cell collapsed)	28 - 178	109	4
10.	Demate: Cell 2 from 1	68 - 106	87	2
	Cell 1 from Frame	88	-	1
11.	RMS transport a module for stowage	66 - 231	158	4
12.	RMS orient a module for stowage	130 - 190	150	4
13.	Stowage of a module	134 - 411	273	2
14.	EVA translate from workstation to frame or frame to workstation	37 - 106	59	10
15.	EVA translate 3 m of a cell	7 - 19	12	24
16.	EVA translate a cell diagonal	12 - 24	18	4
17.	EVA translate along frame (~ 3m)	11 - 18	15	8

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Comparative Tasks (one or two trials of combined events)	(T = Sec) RANGE	(T = Sec) MEAN
A. Deploy all 4 cells simultaneously after locking to frame	285 sec 248 sec	
B. Deploy 2 cells from bay	270 sec 248 sec	
C. Deploy 1 single fold module, 1 EVA with RMS, from frame		0:23:48
D. Deploy 2 single fold modules, 1 EVA with RMS, from frame		0:31:16
E. Deploy 1 double fold module, 1 EVA with RMS, from frame		0:42:12
F. Deploy 2 single fold module, 2 EVA with RMS, from frame		0:45:29
G. Deploy 1 double fold module, 2 EVA with RMS, from frame		0:49:50
H. Deploy 2 single fold modules, 1 EVA with RMS, from bay		0:29:29
I. Deploy 2 single fold modules, 2 EVA with RMS, from bay		0:33:17
J. Deploy 2 double fold modules, 2 EVA with RMS, from bay		0:52:35
K. Retract 2 single fold modules, 2 EVA with RMS, from frame		0:38:13
L. Retract 2 single fold modules, 2 EVA with RMS, from frame		0:23:51
M. Retract 2 double fold modules, 1 EVA with RMS, from frame		0:34:39
N. Retract 2 double fold modules, 1 EVA with RMS, from frame		0:35:00
O. Deploy 2 double fold, 1 from bay, 1 from frame, 2 EVA with RMS		0:47:40
P. Deploy 2 single fold, 1 from bay, 1 from frame, with interconnect, 2 EVA with RMS		0:38:50
Q. Retract 2 single fold with interconnect, 2 EVA with RMS		0:37:33

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MFS-25647